The use of rice fields by wintering ducks : towards mutual benefits for ducks and farmers

Claire Pernollet

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Collège Doctoral du Languedoc-Roussillon

THÈSE

Pour obtenir le grade de Docteur

Délivré par L'UNIVERSITE DE MONTPELLIER

SCIENCES ET TECHNIQUES DU LANGUEDOC

Préparée au sein de l'Ecole Doctorale GAIA,
de l'Unité Avifaune Migratrice de l'ONCFS
et du Département Espèces de la Tour du Valat

Spécialité: Ecologie, Evolution, Ressources Génétiques, Paléobiologie

Présentée par Claire Pernollet

L'UTILISATION DES RIZIÈRES PAR LES CANARDS HIVERNANTS: VERS UNE GESTION DES RIZIÈRES EN INTERCULTURE FAVORABLE AUX CANARDS ET AUX AGRICULTEURS

Soutenue le 24 Février 2016 devant le jury composé de

William SUTHERLAND, Professeur, Université de Cambridge, Royaume-Uni	Rapporteur
Reto SPAAR, Directeur de recherche, Station Ornithologique Suisse, Suisse	Rapporteur
Claude MIAUD, Directeur d'Etude EPHE, CEFE/CNRS, Montpellier, France	Examinateur
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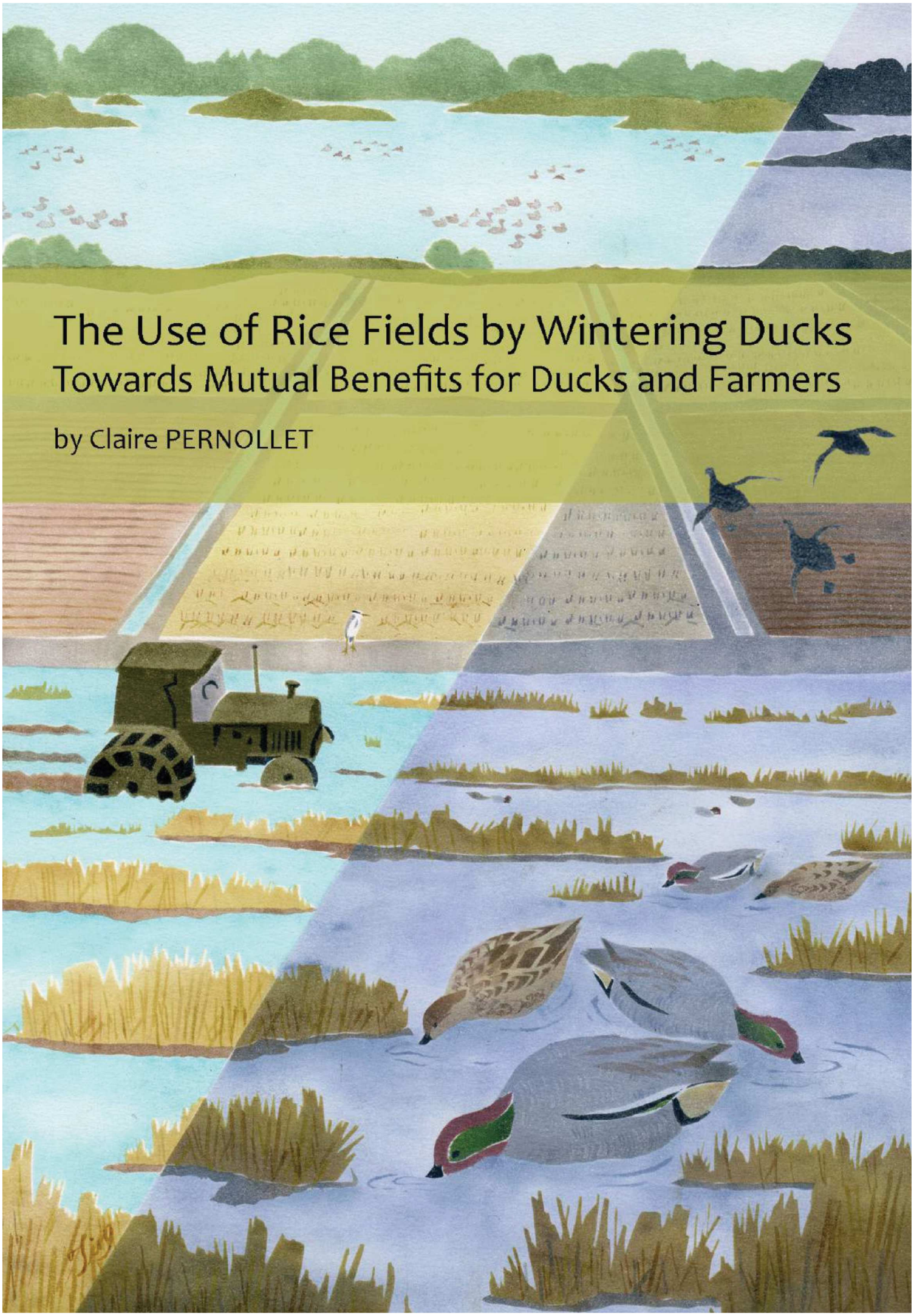
Jean-Claude MOURET, Ingénieur, INRA-UMR Innovation, Montpellier, France	Invité

Office National de la Chasse et de la Faune Sauvage

TOUR DU VALAT



The Use of Rice Fields by Wintering Ducks
Towards Mutual Benefits for Ducks and Farmers

by Claire PERNOLLET

A tous les vilains petits canards qui aiment nager à contre courant
A ceux qui se redressent après la tempête
A ceux qui sont nés pendant cette thèse
A mes deux petits bouts de femmes, Jeannette et Jeanne
A mes parents, « on ira au bout du monde »
A Claudio, porque todo eso valio la pena

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Après le tamisage de 2 684 paquets de terre, l'identification de 135 512 graines, l'élevage de 20 canetons dans la cuisine, le comptage de 32 684 oiseaux lors de 76 sorties diurnes et nocturnes en Camargue et à Doñana, plus de 50 000 km parcourus entre Vercelli, Wilhelmshaven, Tokyo, Séville, San Francisco et České Budějovice, 36 cheveux blancs et 1 kg d'ongles grignotés ce que je retiens avant tout de ces trois ans est l'aventure humaine. J'espère que le compte sera bon et que je n'oublierai personne. D'avance pardon si ce n'est pas le cas.

Ma mère dit toujours avec une pointe d'humour qu'elle a passé son bac à quatre (« A4 », nom donné au bac littéraire à son époque). En énumérant les prénoms de ceux qui ont participé activement, je peux affirmer que j'ai fait une thèse « A 29». Cette thèse est un orchestre sans chef issu de l'association de cerveaux bien pensants et surtout d'une sacrée bande de joyeux lurons, de personnages, tous aussi intéressants les uns que les autres.

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PREFACE/PRÉFACE

The general context

This dissertation concludes a 3-years doctoral work at the Centre de Recherche de la Tour du Valat (http://www.tourduvalat.org), Camargue, France, under the supervision of Dr. Matthieu Guillemain (ONCFS) and Dr. Michel Gauthier-Clerc (Associate researcher at Tour du Valat, current director of the Garenne Zoo, Switzerland), and in collaboration with numerous other scientists. I worked for the Migratory Bird Unit of the Office National de la Chasse et de la Faune Sauvage (ONCFS) and the Species Department of the Centre de Recherche de la Tour du Valat from January 2013 to February 2016. This is with the exception of a 6-weeks stay in the Department of Wetland Ecology, Estación Biológica de Doñana, Spain, during November 2014, under the supervision of Dr. Andrew Green and Dr. Jordi Figuerola, and a 3-weeks stay at the Wildlife, Fish, and Conservation Biology Faculty of the University of California, Davis, United States, during February 2015, under the supervision of Pr. John Eadie. These two foreign internship opportunities (to carry out fieldwork and modelling work) were added to the initial project in order to let me discover other ways of doing research, and to reinforce professional links to prepare future research after the PhD. The outcomes of these training periods do not properly appear in the current manuscript. These are projects we have started to implement during this PhD, and plan to develop further in the near future. These data are still being analysed, so that the results are therefore not included in the current thesis.

The core of my research was financially supported by the Centre de Recherche de la Tour du Valat and an ONCFS PhD grant. Part of the United States internship was financed by a scholarship for international mobility from the SIBAGHE (current GAIA) doctoral school, Montpellier University, France.

Thesis contents and structure

The initial focus of the project was the use of post-harvest rice fields by wintering ducks and the influence of agricultural practices on such use. With time, this topic was gradually widened to a more global questioning about the general management of rice fields and the opportunities to provide mutual benefits for wintering ducks and farmers. The structure of the thesis manuscript reveals such gradual progress in the thinking, and the will to cover aspects ranging from purely ecological questions (e.g. variation in the energy density of seeds available to ducks across the winter) to an assessment of the agronomical and economical realism of such suggested procedures, as well as a future proper test of management procedures via modelling.

This dissertation consists of six parts. First, a synthesis of the thesis in French is provided, second a general introduction presents the theoretical framework within which research was carried out, and introduces the main hypotheses and questions. Three chapters then constitute the core of the thesis and aim at providing answers to these questions, via empirical fieldwork and experimental tests. The first chapter is a review of the literature focusing on waterfowl and ricefield relationships worldwide; the second chapter studies the influence of post-harvest practices on seed availability and duck use; the third chapter concentrates on the potential agronomic benefits provided by ricefield winter flooding and ducks attracted in flooded rice fields. Finally, a general discussion comprising the economic

analysis leads from waterbird ecology to more general habitat conservation issues and innovative agricultural management perspectives.

The main papers are enclosed into their respective chapters. The main results of each are linked together in a short introductive text at the beginning of the corresponding chapter (except for two introductive papers not directly linked to the main topic, which can be found in the Appendices together with the paper from the economic analysis). The Appendices also comprise the list of communications made at scientific conferences during the PhD, as well as the popularisation documents prepared for farmers and land managers from the scientific results.

It is my hope that this research will serve rice producers, decision makers, wildlife researchers, land managers, students, and outdoor enthusiasts alike to promote compatibility between wildlife conservation and human activities.

I hope the reading will be enjoyable.

LIST OF PAPERS/ LISTE DES PUBLICATIONS

This dissertation is based on the following papers:

CHAPTER I.
STATE-OF-THE-ART ON RICE FARMING AND DUCK CONSERVATION

Article 1: p 55

Pernollet C.A., Simpson D., Gauthier-Clerc M., Guillemain M. 2015. Rice and Duck, a good combination? Identifying the incentives and triggers for joint rice farming and wild duck conservation. *Agriculture, Ecosystems and Environment*, **214**: 118-132. DOI: http://dx.doi.org/10.1016/j.agee.2015.08.018. I.F.: 3.20.

CHAPTER II.
INFLUENCE OF POST-HARVEST PRACTICES ON SEED AVAILABILITY AND DUCK USE

Article 2: p 102

Pernollet C.A., Guelmami A., Green A.J., Curcó Masip A., Dies B., Bogliani G., Tesio F., Brogi A., Gauthier-Clerc M., Guillemain M. 2015. A comparison of wintering duck numbers among European rice production areas with contrasting flooding regimes. *Biological Conservation* **186**: 214-224. DOI : 10.1016/j.biocon.2015.03.019. I.F.: 4.04.

Article 3: p 114

Pernollet C.A., Cavallo F., Simpson D., Gauthier-Clerc M., Guillemain M. (*under revision).* Seed availability and waterfowl use of ricefields in Camargue (France): the role of post-harvest practices*. Journal of Wildlife Management.* I.F.: 1.61.

CHAPTER III.
POTENTIAL AGRONOMIC BENEFITS OF RICEFIELD WINTER FLOODING AND DUCK USE OF FLOODED FIELDS

Article 4: p 147

Pernollet C.A., Mesléard F., Robin J-P., Hanzen C., Rutter I., Cavallo F., Gauthier-Clerc M., Guillemain M.**,** (*in preparation*). Effect of winter flooding on deterioration of rice and main rice weed seeds: a greenhouse experiment. *Freshwater Biology*. I.F.: 2.74.

Article 5: p 165

Brogi A., Pernollet C.A., Gauthier-Clerc M., Guillemain M. 2015. Waterfowl foraging in winter-flooded ricefields: Any agronomic benefits for farmers? *Ambio*, **44**: 793-802. DOI : 10.1007/s13280-015-0678-0 I.F.: 2.97.

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APPENDIX I. ADDITIONAL PAPERS

Appendix I.1: p 206

Article 6:

Niang A., Pernollet C.A., Gauthier-Clerc M., Guillemain M. (*submitted*). A cost-benefit analysis of ricefield winter flooding for conservation purposes in Camargue, Southern France. *Agriculture, Ecosystems and Environment.* I.F.: 3.20.

Appendix I.2: p 232

Guillemain M., Pernollet C.A., Massez G., Cavallo F., Simon G., Champagnon J. 2015a. Disentangling the drivers of change in Common Teal migration phenology over 50 years: land use vs. climate change effects. *Journal of Ornithology* **156**, 647-655. DOI : 10.1007/s10336-015-1171-z. I.F.: 1.93.

Appendix I.3: p 242

Guillemain M., Champagnon J., Massez G., Pernollet C.A., George T., Momerency A., Simon G. 2015b. Becoming sedentary? Changes in Mallard *Anas platyrhynchos* ring recovery locations over the last 50 years. *Wildfowl* **65**: 51-63.

APPENDIX II. SCIENTIFIC COMMUNICATIONS: p 256

Appendix II.1 Oral communications

Appendix II.2 Posters

APPENDIX III. POPULAR COMMUNICATIONS: p 261

Appendix III.1 Oral communications

Appendix III.2 Grey literature

We thank the journal editors for pemitting the reproduction of original published papers.

SYNTHÈSE EN FRANÇAIS

Rizières de Camargue en hiver, Michel Gauthier-Clerc

Rizières du Delta de l'Ebre en hiver, Juan Carlos Cicera

INTRODUCTION

I. Les agroécosystèmes: menaces et opportunités

I.1 L'Agroécosystème, comme un élément intégré dans le paysage

L'expansion et l'intensification de l'agriculture sont reconnues comme étant deux importantes menaces pour la biodiversité et le bon fonctionnement des écosystèmes (Donald et al., 2006). Face à l'augmentation croissante de la demande alimentaire (Tilman et al., 2001), **des mesures d'urgence doivent être prises afin d'assurer la durabilité de la production agricole**.

Couvrant 24% de la surface terrestre et plus de 45% de l'Europe (Henle et al., 2008), les systèmes cultivés dominent le paysage (MEA, 2005). La moitié des terres agricoles et 60% des services écosystémiques (à savoir les services d'approvisionnement, de support, de régulation et les services culturels rendus par les écosystèmes) sont dégradés (MEA, 2005). Compte tenu du rôle écologique de la biodiversité fonctionnelle pour la production agricole (Altieri, 1999), **il est nécessaire de gérer les paysages agricoles de manière à également promouvoir la biodiversité** (Scherr et McNeely, 2008).

La production de ressources a été historiquement considérée comme l'unique service rendu par les paysages agricoles (service d'approvisionnement). Toutefois ces paysages ont rarement été identifiés comme producteurs de services de support, de régulation ou culturels (Power, 2010). Au contraire, les agroécosystèmes sont souvent identifiés comme source destructrice des services fournis par les écosystèmes naturels, alors qu'ils en dépendent largement pour leur propre entretien (Power, 2010). **Dans quelle mesure les agroécosystèmes interagissent avec les habitats naturels et peuvent ou non fournir des services autres que la production agricole dépend largement de la façon dont ils sont gérés** (Altieri, 1999; Swift et al., 2004; Power, 2010).

Du point de vue agronomique, la présence de la biodiversité fonctionnelle dans les champs cultivés peut être encouragée par l'agro-écologie ou la gestion intégrée des adventices et des ravageurs de culture (Shennan et al., 2008). Ces approches considèrent qu'une meilleure intégration des mécanismes écologiques, émergeant de l'étude des écosystèmes naturels, peut fournir des indications sur la façon dont les interactions biotiques déterminent les fonctions des agroécosystèmes (Ormerod et al., 2003). La tendance est aujourd'hui aux études visant à combler le fossé entre l'agronomie et l'écologie par **la promotion de mesures de gestion qui favorisent les interactions biotiques bénéfiques et minimisent les indésirables dans les agroécosystèmes** (Shennan et al., 2008).

Le concept d'**« intensification écologique »** implique la protection des services écosystémiques pour une agriculture durable, et l'augmentation de la production alimentaire dans les terres agricoles déjà existantes. Son développement a été identifié comme l'une des priorités de conservation pour 2015 (Sutherland et al., 2015).

I.2 Pertinence du modèle canard-riziculture

Les rizières couvrent environ 1% de la surface du globe (FAO-STAT, 2013) et représentent 15% de la surface totale en zones humides (Lawler, 2001). Elles sont **une menace pour les zones humides naturelles** (conversion, agriculture intensive) mais ont également été reconnues par la Convention de Ramsar comme **un écosystème important pour la biodiversité** (Dean-Speirs et al., 2010).

La capacité des rizières à atténuer la perte des zones humides naturelles est largement discutée, principalement en Méditerranée (ex : Tourenq et al., 2001; Toral et Figuerola, 2010). Dans cette région, 80 à 90% des zones humides naturelles ont disparu (Finlayson et al., 1992) et environ 23% des zones humides restantes sont artificielles (Perennou et al., 2012). L'importance des rizières pour la conservation des oiseaux d'eau est aussi largement reconnue (Czech et Parsons, 2002; Elphick et al., 2010), y compris en Europe (Longoni et al., 2010; Sánchez-Guzmán et al., 2007).

Contrairement aux passereaux (Pain et Pienkowski, 1997; Wilson et al., 2009), les conséquences des pratiques agricoles sur les populations d'Anatidés, en particulier de canards, ont reçu une attention moindre (Thomas, 1982, Van Eerden et al., 1996; Duncan et al., 1999), alors que cette famille d'oiseaux fournit **de nombreux services écosystémiques** (Green et Elmberg, 2014). Les bénéfices agronomiques potentiellement apportés par les Anatidés aux riziculteurs ont surtout été étudiés en Amérique du Nord (Anders et al., 2008). En Europe, les questions de tels services écosystémiques n'ont été abordées que récemment, à travers une étude sur le recyclage des nutriments par les oiseaux d'eau (Navedo et al., 2015). Une des explications probables à ce manque de connaissance est liée au fait que les canards européens utilisent principalement les terres agricoles comme sites d'alimentation nocturne (Tamisier et Dehorter, 1999; Pirot, 1981; Mesléard et al., 1995), ce qui rend souvent difficile leur observation.

Près d'un quart des espèces d'Anatidés est actuellement menacé (Wetlands International, 2013). Green (1996) a identifié la perte de zones humides comme principale cause de déclin. De leur côté, Long et al. (2007) ont identifié les changements de gestion des terres agricoles comme principale menace. **La plupart des zones rizicoles européennes sont souvent situées à proximité des plus grands quartiers d'hivernage de canards. Une gestion appropriée de ces espaces pourrait participer à leur conservation**. Les Anatidés utilisant surtout les rizières pour leur alimentation, l**'approvisionnement en ressources suffisamment abondantes et accessibles déterminera donc l'utilisation de ces habitats par ces oiseaux.**

I.3 L'intensification de l'agriculture et le déclin des oiseaux des terres cultivables en Europe: une question de ressources pour les granivores

En raison de l'intensification des cultures ou de l'abandon des terres, les activités agricoles sont actuellement responsables d'une perte massive de biodiversité, menaçant entre autres les oiseaux. La Politique Agricole Commune (PAC) mise en place après la seconde guerre mondiale pour moderniser le secteur et augmenter la productivité agricole a été la force motrice derrière l'intensification et la spécialisation des cultures arables en Europe (Pain et Pienkowski, 1997; Donald et al., 2001). L'utilisation accrue d'engrais et de pesticides, la mécanisation, la simplification des rotations de cultures et la perte de nombreux éléments naturels (par exemple des haies) ont conduit à une réduction de la diversité des paysages, à la

dégradation des sols, à la pollution de l'eau et à la perturbation de la chaîne alimentaire (Stoate et al., 2001), affectant à la fois la flore (Marshall et al., 2003) et les populations animales (Wilson et al., 1999). En conséquence, depuis les années 1970 les oiseaux des terres agricoles ont diminué en abondance plus que toute autre communauté d'avifaune en Europe (Donald et al., 2001; 2006). Environ la moitié de ces espèces est aujourd'hui en déclin ou menacée (Pain et Pienkowski, 1997).

Afin d'enrayer ces baisses d'effectifs, il est nécessaire d'acquérir une bonne compréhension de l'utilisation de l'habitat par les espèces ainsi que d'identifier les facteurs limitants et les possibles mesures de gestion de l'habitat (Sutherland et Hill, 1995; Fuller, 2012). Bien que chaque espèce puisse répondre de manière particulière aux changements de pratiques agricoles, certains groupes d'espèces partagent des facteurs de causalité communs de déclin (Newton, 2004). Par exemple, le déclin des oiseaux des terres agricoles a été associé à une réduction de la disponibilité des ressources en graines pendant la saison hivernale (Wilson et al., 1999; Moorcroft et al., 2002; Robinson et Sutherland, 2002).

L'abondance et l'accessibilité déterminent conjointement **la disponibilité des ressources alimentaires** et agissent comme facteurs clés limitant la valeur sélective des consommateurs ainsi que la taille de leurs populations (Newton, 1998). Comprendre la dynamique des ressources alimentaires dans un habitat est important pour déterminer sa capacité d'accueil potentielle pour les oiseaux et les autres consommateurs. La capacité d'accueil a été classiquement définie comme le nombre maximum d'individus-jours que peut supporter un habitat étant donné les ressources alimentaires qu'il contient (Goss-Custard et al., 2003). Pour les les espèces qui nous intéressent, la capacité d'accueil a été définie par le nombre de canards-jours (duck-use-days, DUD) (Reinecke et al., 1989). Le DUD est le nombre de canards qui peuvent survivre pendant une journée sur un hectare d'habitat. Il est calculé à partir de la formule suivante:

$$\text{DUD} = \frac{[\text{nourriture disponible (g de matière sèche)} * \text{énergie métabolisable (kcal/ g de matière sèche)}]}{[\text{besoins énergétiques quotidiens d'un oiseau (kcal/jour)}]}$$

Une gestion appropriée de l'habitat hivernal permettant une plus grande disponibilité des ressources constitue un moyen d'accroître sa capacité d'accueil (Ma et al., 2010), comme cela peut être le cas pour les canards hivernants dans les rizières.

I.4 De la science à la politique à la science: la mise en œuvre des mesures agro-environnementales au cours de la période hivernale

Les mesures agro-environnementales (MAE) mises en place au milieu des années 1980 par la communauté européenne sont l'instrument politique le plus important pour contrer les effets négatifs de l'agriculture moderne sur l'environnement. Elles permettent aux agriculteurs de recevoir des incitations financières pour l'adoption de pratiques respectueuses de l'environnement (EC General Directorate for Agriculture and Rural Development, 2005).

Plusieurs MAE ont été mises en place afin de maximiser les ressources en graines dans une tentative d'enrayer le déclin des oiseaux granivores (ex : couverts faune sauvage, Stoate et al., 2004, agrainage, Siriwardena et al., 2007, non-labour du sol, Cunningham et al., 2005). Le maintien des chaumes s'est aussi montré efficace pour l'augmentation des populations d'oiseaux des terres agricoles (Sutherland, 2015).

Des sommes d'argent conséquentes sont dépensées chaque année dans le cadre des MAE (UE: 3,7 milliards € en 2003, Kleijn et al., 2006). Ceci nécessite donc une évaluation par les gouvernements de l'efficacité des mesures mises en place; une question largement débattue par la communauté scientifique (Kleijn et Sutherland, 2003; Kleijn et al., 2006).

II. Canards et riziculture dans le paysage camarguais: structure et objectifs de la thèse

L'objectif de cette thèse était d'évaluer s'il existe **des pratiques inter-culturales « gagnant-gagnant » pour les riziculteurs et pour la conservation des canards hivernants dans les zones de production intensive du riz en Europe et plus particulièrement en Camargue** (France).

II.1 Etat de l'art: riziculture et conservation des Anatidés

La littérature sur les canards sauvages et la production rizicole est disproportionnellement représentée par des etudes réalisées aux Etats-Unis se concentrant sur la gestion des rizières en interculture en tant qu'habitat d'alimentation pour les oiseaux sauvages hivernants (Eadie et al., 2008). Les études en Asie sont au contraire plutôt focalisées sur les avantages agronomiques apportés par l'élevage de canards de ferme dans les systèmes d'agriculture intégrée « riz-canard » (Furuno, 2001). Ce travail vise, à travers une approche combinant agronomie et écologie, à identifier les pratiques post-récolte offrant le plus de services écosystémiques. Pour atteindre ce but, nous avons d'abord réalisé une revue bibliographique pour établir l'état de l'art sur la conservation des canards et la production rizicole dans le monde, compte tenu en particulier des études américaines et asiatiques (**Chapitre I, Article 1**).

L'hypothèse que nous cherchions à tester était qu'**il existe des mesures de gestion qui favorisent les interactions bénéfiques entre les canards sauvages et la production rizicole, et minimisent celles qui sont indésirables.**

II.2 Paysages rizicoles et pratiques post-récolte bénéfiques aux canards

L'objectif spécifique du **Chapitre II** était de caractériser les pratiques agricoles post-récolte pratiquées dans les principales régions rizicoles d'Europe, qui appartiennent à la voie de migration Est-Atlantique et d'identifier celles qui favorisent la disponibilité des ressources en graines et la présence de canards en Camargue (France).

L'impact de la gestion de la paille sur la disponibilité en graines et l'utilisation des rizières par les canards ont été étudiés aux États-Unis (Eadie et al., 2008; Elphick et al., 2010). La quantité de résidus de culture disponible pour les Anatidés y est réduite par l'utilisation de variétés de riz à croissance rapide (Stafford et al., 2010), l'utilisation de moissonneuses batteuses modernes (Fleskes et al., 2012) et le labour (Stafford et al., 2010). On ignore toujours dans quelle mesure la gestion de la paille (brûlage, broyage, déchaumage) peut influencer l'utilisation des champs par les canards (Elphick et al., 2010). Cependant, l'efficacité de l'inondation hivernale pour attirer les canards dans les rizières a été démontrée, tant aux États-Unis qu'au Japon (Elphick et Oring, 2003; Tajiri et Ohkawara, 2013).

C'est sur la base de ces connaissances qu'une MAE "inondation hivernale des rizières" a été mise en place pour les oiseaux d'eau sur des sites Ramsar espagnols (Albufera de Valencia, Delta de l'Ebre) au début des années 2000. Elle consiste à maintenir les surfaces de rizières inondées pendant 3,5 à 4 mois l'hiver. L'extension de l'utilisation de cette pratique en Europe et la réponse des populations d'oiseaux d'eau à cette MAE n'avaient jusqu'à présent pas été évaluées.

Sur la base de ces résultats, les hypothèses testées dans ce chapitre étaient les suivantes:

- Le nombre de canards dans les principales régions rizicoles d'Europe de l'Ouest est positivement corrélé à la superficie en rizières inondées en hiver (Article 2).

- La MAE « inondation hivernale des rizières » engendre un plus grand nombre de canards hivernants sur les sites espagnols (Article 2).

- La disponibilité des ressources en graines dans les rizières est affectée négativement par le labour (Article 3).

- L'inondation hivernale des rizières est le principal facteur expliquant l'utilisation des rizières par les canards hivernants (Article 3).

Nous avons comparé les paysages agricoles de cinq grandes régions rizicoles d'Europe occidentale, appartenant toutes à la même voie de migration (Est-Atlantique, voir délimitations des voies de migration dans Scott et Rose, 1996), et la relation entre leurs paysages et le nombre de canards hivernants qu'elles hébergent. Nous avons considéré les six espèces européennes les plus communes de canards de surface: le canard colvert *Anas platyrhynchos*, la sarcelle d'hiver *A. crecca*, le canard pilet *A. acuta*, le canard souchet *A. clypeata*, le canard siffleur *Mareca penelope* et le canard chipeau *M. strepera* (**Article 2**). Après cette analyse à l'échelle internationale, nous avons étudié plus précisément la disponibilité en ressources et l'utilisation des rizières par les canards en fonction des pratiques post-récolte (brûlage, broyage, inondations, labour) en Camargue (**Article 3**).

II.3 Bénéfices agronomiques potentiels de la mise en eau hivernale des rizières et de l'attraction des canards dans ces dernières

Le **Chapitre III** traite des services écosystémiques potentiels apportés aux agriculteurs par l'inondation hivernale des rizières et l'attraction des canards dans ces dernières. Il aborde à travers des tests expérimentaux les principaux problèmes agronomiques que doivent affronter les riziculteurs: la gestion des adventices (services de régulation) et celle de la paille (services de support).

Des études antérieures ont montré que l'inondation des rizières en hiver peut améliorer la décomposition de la paille et réduire la biomasse d'adventices (Manley et al., 2005) ou la viabilité de leurs graines (Fogliatto et al., 2010; Baek et Chung, 2012). Ces effets qui peuvent être accentués par la présence de canards sauvages s'alimentant sur ces rizières (Bird et al., 2000, van Groenigen et al., 2003). En parallèle, d'autres études ont indiqué que l'élevage des canards sur les rizières en Asie empêche la croissance de nombreuses adventices et réduit leur biomasse par piétinement et consommation des jeunes plants et des graines (Furuno, 2001).

Sur la base de ces résultats, nos hypothèses étaient les suivantes:

-L'inondation hivernale des rizières est une gestion biologique efficace pour contrôler les adventices de riz grâce à l'augmentation de la dégradation des graines (Article 4)

-Les canards attirés dans les rizières inondées après la récolte profitent aux agriculteurs à travers la réduction de la banque de graines et la réduction des chaumes de riz (Article 5)

Les rizières de Camargue sont traditionnellement inondées d'avril à septembre, entre le semis et la récolte, puis gardés en chaumes, déchaumées ou labourées pendant l'hiver (Mañosa i Rifé, 1997). Actuellement, environ 75% des résidus de paille de riz sont brûlés; le reste étant broyé (Monier et al., 2009). L'écobuage de la paille est toléré par dérogation, mais des préoccupations croissantes concernant la pollution de l'air engendrée pourraient bientôt provoquer des décisions politiques qui limiteraient ou interdiraient complètement cette pratique (Couderc, 2013). Dans ce contexte, des modes de gestion de la paille alternatifs sont donc nécessaires. La petite proportion de rizières inondées en hiver en Camargue l'est surtout à des fins cynégétiques (Mathevet et Mesléard, 2002). Le désherbage est aussi une préoccupation pour les riziculteurs français, car les conditions climatiques et un accès plus limité aux pesticides en France rendent la production de riz moins compétitive que celle des Espagnols ou des Italiens. En outre, le plan national Ecophyto décidé lors du Grenelle de l'Environnement (2007) vise à réduire de 50% l'utilisation des pesticides d'ici à 2018. Dans ces conditions, l'inondation des rizières en hiver peut apparaître comme une technique alternative pour limiter simultanément les adventices et dégrader les chaumes. Nous avons évalué expérimentalement la détérioration sous serre du riz et des graines d'adventices au cours d'un hiver en conditions sèches ou inondées (**Article 4)**. Nous avons également testé en enclos en plein champ l'effet des canards hivernants et des canards d'élevage sur la banque de graines et sur les chaumes après un hiver (**Article 5**).

II.4 Evaluation économique de l'inondation hivernale en Camargue

L'évaluation économique des services écosystémiques est préconisée par un nombre croissant d'écologues ; comme une stratégie à court terme pour communiquer sur la valeur de la biodiversité dans une langue qui reflète les opinions politiques et économiques dominantes. Elle peut aussi fournir des indications complémentaires aux résultats purement écologiques (Turner et al., 2000). Pour conclure le raisonnement développé dans les **Chapitres II** et **III**, nous avons effectué une analyse coûts-bénéfices pour évaluer la pertinence de l'inondation des rizières en hiver en France (**Article 6, Annexe I.1**).

Nos hypothèses étaient les suivantes:

–L'inondation hivernale des rizières en Camargue est économiquement réaliste pour l'agriculteur (Article 6, Annexe I.1)

– L'inondation hivernale des rizières en Camargue est économiquement réaliste et souhaitable du point de vue de la société locale (Article 6, Annexe I.1)

CHAPITRE I. ÉTAT DE L'ART: RIZICULTURE ET CONSERVATION DES ANATIDÉS

I.1 Contexte général

Les revues de la littérature sont une source importante d'information scientifique pour les gestionnaires et les décideurs, leur permettant d'évaluer l'efficacité d'interventions de gestion ou de politiques de conservation (ex: Pullin et al., 2004; Pullin et Stewart, 2006; Roberts et al., 2006).

Cette revue bibliographique (**Article 1**) expose les interactions positives et négatives entre les rizières et les canards (sauvages et d'élevage) dans le monde, dans une perspective plus large que le seul sujet de la thèse, qui elle se concentre sur une zone géographique, la Camargue, et une période, l'hiver. Elle fournit une compréhension générale du contexte dans lequel les questions de la thèse sont développées. Elle met aussi en en évidence des leviers, freins et manques de connaissances ainsi que les mesures de gestion à mettre en place pour diminuer les contraintes et améliorer les bénéfices.

Pour la réalisation de cette revue, nous avons tenté de suivre l'approche d'une revue systématique comme le Centre for Evidence-Based Conservation (http://www.conservationevidence.com) et le Collaboration for Environmental Evidence (www.environmentalevidence.org) le conseillent. Ceci a impliqué 1) une recherche systématique de la littérature combinant plusieurs sources d'information (revues de littérature, articles scientifiques, littérature grise d'organisations non-gouvernementales, de gouvernements et d'experts clés), 2) une présentation des données chiffrées sous la forme de tableaux et graphiques et 3) une exposition claire des données et résultats utiles à la conservation, une identification des lacunes dans les données et une liste de conseils de gestion (cf. tous les critères dans Roberts et al., 2006).

I.2 Résultats clés

Nous soulignons ici uniquement les résultats concernant l'option de gestion qui semble la plus favorable aux canards et aux riziculteurs et a ensuite été testée durant le reste de ce travail de thèse, à savoir l'inondation hivernale des rizières (**Article 1**).

Une batterie de résultats a montré que l'inondation hivernale:

-Améliore l'accessibilité des canards aux ressources alimentaires dans les rizières. Une telle gestion augmente instantanément le nombre de canards s'alimentant ainsi que la fréquentation globale des rizières (ex: Day et Colwell, 1998; Shimada et al., 2000; Elphick et Oring, 2003;. Havens et al., 2009; Tajiri et Ohkawara, 2013).

-Offre des avantages agronomiques aux agriculteurs grâce à l'augmentation du recyclage des éléments nutritifs (Manley et al., 1999; Eagle et al., 2000), de la décomposition de la paille (Manley et al., 2005) et de la réduction de la viabilité des graines d'adventices (Street et Bollich, 2003; Manley et al., 2005; Fogliatto et al., 2010; Baek et Chung, 2012) (ex : Anders et al, 2008 et Tableau 2 de **l'Article 1**).

-A son action accentuée par **les canards attirés** dans les rizières inondées, qui **peuvent également accroître la décomposition de la paille et diminuer la biomasse d'adventices au printemps** (ex: Bird et al., 2000; Van Groenigen et al., 2003; Van Diepen et al., 2004 et Tableau 2 de **l'Article 1**).

La revue de la littérature a aussi souligné certains manques de connaissances:

-1) Elphick et al. (2010b) ont signalé que l'on ignore comment la gestion de la paille peut influencer l'utilisation des rizières par des canards.

-2) Les comptages nocturnes existants (Rave et Cordes, 1993; Cox et Afton, 1997; Tamisier et Dehorter, 1999; Pirot, 1981; Mesléard et al, 1995) ont révélé que l'utilisation que font les canards des rizières en chaume est importante et mérite un meilleur suivi. La plupart des comptages existants sont pourtant diurnes (Twedt et Nelms, 1999; Tourenq et al., 2001;Elphick et Oring, 2003).

-3) La disponibilité de toutes les sources de nourriture pendant l'hiver (Manley et al., 2004; Stafford et al., 2006; Greer et al., 2009; Stafford et al., 2010), la quantité d'énergie fournie par ces ressources (Kaminski et al., 2003) et la variabilité de l'énergie au cours de l'hiver. (Nelms et Twedt, 1996) nécessitent une estimation plus précise pour une meilleure évaluation de la capacité d'accueil des rizières.

-4) King et al. (2010) considèrent que des études au niveau du paysage rizicole sont nécessaires afin de mettre en œuvre des plans de conservation à des échelles plus grandes, impliquant à la fois les zones humides naturelles et les terres agricoles inondées. Mieux comprendre les facteurs à l'origine des mouvements des canards entre les zones humides naturelles et artificielles, ainsi qu'entre leur remise diurne et leurs sites d'alimentation nocturnes, permettrait une meilleure évaluation de l'effet des caractéristiques du paysage et de son hétérogénéité sur ces espèces (Chan et al., 2007; Elphick, 2008).

-5) Stafford et al. (2010) ont appelé les chercheurs à employer des outils modernes de télédétection pour étudier l'évolution des surfaces cultivées en riz à travers le monde. D'autres outils modernes de modélisation tels que les modèles énergétiques ou les modèles multi-agents (Amano et al., 2006; Petrie et al., 2014; Miller et al., 2014) permettraient de prédire les mouvements et l'utilisation des rizières par les canards hivernants, et de fournir des informations pour guider de futurs plans de conservation.

-6) Eadie et al. (2008) et Anders et al. (2008) estiment nécessaire une évaluation économique précise des coûts et bénéfices de l'inondation hivernale des rizières considérant les coûts agronomiques évités, des opérations de travail du sol, de pompage de l'eau, mais également les bénéfices d'un potentiel revenu de la chasse ou d'activités écotouristiques.

I.3 Liens avec les prochains chapitres de la thèse

Nous avons utilisé les principaux résultats de la revue bibliographique (**Article 1**) afin de guider les études empiriques et expérimentales mises en place sur le terrain et au laboratoire au cours de cette thèse, en essayant de couvrir une partie des manques de connaissances énumérés ci-dessus et nécessitant de plus amples recherches:

-Des comptages nocturnes de canards ont été réalisés dans les rizières de Camargue soumises à différentes pratiques post-récolte (**Article 3**, couvrant les points 1 et 2 ci-dessus).

-La disponibilité en graines après la récolte et la déplétion des ressources en graines au cours de l'hiver ont été étudiées en Camargue, ce qui a permis d'estimer avec précision le Duck Use-Days (**Article 3**, couvrant le point 3 ci-dessus).

-Le contenu énergétique et la dégradation des graines d'adventices au cours de l'hiver ont été évalués de manière expérimentale (**Article 4**, couvrant le point 3 ci-dessus).

-La télédétection a été utilisée pour étudier cinq paysages rizicoles européens (**Article 2**) et une première mise en application du modèle multi-agents SWAMP est actuellement prévue en Camargue (projet SWAMP présenté en discussion) (couvrant les points 4 et 5 ci-dessus).

-Une évaluation complète des coûts et bénéfices de l'inondation hivernale en Camargue a été effectuée afin de déterminer si une telle gestion serait économiquement acceptable par les agriculteurs et la société en Camargue (**Article 6, Annexe 3** couvrant le point 7 ci-dessus).

CHAPITRE II. INFLUENCE DES PRATIQUES EN INTERCULTURE SUR LA DISPONIBILITÉ DES GRAINES ET L'UTILISATION DES RIZIÈRES PAR LES CANARDS

II.1 Contexte général

Le **Chapitre II** vise à déterminer quelles sont les pratiques en interculture les plus appropriées pour fournir un habitat d'alimentation aux canards hivernants dans les zones rizicoles européennes.

Nous avons mis l'accent sur l'inondation hivernale des rizières, identifiée dans le **Chapitre I** (**Article 1**) comme la mesure de gestion la plus favorable aux canards et aux riziculteurs. Nous avons évalué l'utilisation de cette pratique en Europe de l'Ouest sur cinq grandes régions rizicoles (**Article 2**), puis les conséquences de différentes pratiques en interculture sur la disponibilité des ressources en graines et la fréquentation de ces habitats par les canards spécifiquement en Camargue (**Article 3**).

Des études antérieures ont porté sur la disponibilité des ressources alimentaires et la fréquentation nocturne des rizières et marais peu profonds par les canards (Tamisier et Dehorter, 1999; Pirot, 1981; Mesléard et al., 1995). Elles ont suggéré que les rizières inondées représentaient un habitat d'alimentation important pour les canards granivores. Par opposition à ces auteurs, Tourenq (2000) a conclu que seulement 6% des rizières de Camargue étaient inondées pendant l'hiver (environ 10% d'après Pirot, 1981) et ne constituaient pas un habitat très important pour ces oiseaux. Une mise à jour du degré d'utilisation de l'inondation hivernale et de la fréquentation des rizières par les canards en hiver était donc nécessaire.

II.2 Résultats clés

Les études présentées dans les articles de ce chapitre fournissent de nouveaux résultats scientifiques qui peuvent être utiles à la conservation des zones humides et des oiseaux d'eau, car ils ont permis:

1/ d'obtenir une évaluation actualisée de l'état de conservation des zones humides et de l'utilisation de l'inondation hivernale des rizières dans de grandes régions rizicoles européennes, ainsi que de mesurer la contribution de ces éléments du paysage pour la conservation des canards. Les cinq régions d'étude présentent des paysages très contrastés en terme de proportions de surfaces couvertes par les zones humides naturelles et les rizières.

Les pratiques post-récolte diffèrent aussi grandement ; la proportion de rizières inondées en hiver variant de 0,17 à 62%. En Camargue, seuls 9% des rizières sont inondés, à des fins cynégétiques. Le rôle des différences d'incitation financière (MAE) dans l'existence de telles disparités à l'échelle européenne est évalué (**Article 2**).

2/ de rouvrir le débat sur les complémentarités entre zones humides et champs de riz. L'abondance de canards hivernants est positivement liée à la présence de zones humides au sens large, c'est-à-dire à la somme des surfaces en zones humides naturelles et des rizières inondées (**Article 2**).

3/ d'estimer la disponibilité en graines dans les rizières après la récolte, et leur déplétion au cours de l'hiver. Une demi-tonne de graines en moyenne était disponible après récolte à la surface d'environ 50 rizières échantillonnées en Camargue au cours des hivers 2012-2013 et 2013-2014 (riz: 349,9 kg/ha ± 57,6 SE; adventices: 141,6 kg/ha ± 21,3 SE). L'abondance de cette ressource alimentaire ne dépendait pas de la gestion de la paille (brûlure, broyage ou déchaumage) mais diminuait fortement au cours de l'hiver (-89% pour le riz et -69% pour les adventices) ; cette déplétion étant accentuée par la pratique d'un labour (**Article 3**).

4/ d'examiner l'influence des pratiques en interculture sur l'utilisation des rizières par les canards. L'inondation des rizières en hiver est le principal facteur explicatif de la présence de canards sur les rizières (**Articles 2** et **3**). L'abondance de canards sur les zones rizicoles européennes était plus grande dans les régions où plus de rizières étaient inondées après récolte (**Articles 2)**. L'inondation hivernale était également le principal facteur explicatif de la fréquentation nocturne des rizières par les canards en Camargue (24 canards/ha en moyenne dans les parcelles inondées et 0,3 dans les sèches) (**Articles 3)**. Aucun effet évident de la gestion post-récolte sur la fréquentation des rizières par les canards n'a été détecté tant que les champs étaient inondés (**Articles 3)**.

5/ de tester l'efficacité de la mesure agri-environnementale « inondation hivernale des rizières » en Espagne. Depuis la mise en place de cette MAE au début des années 2000, les deux régions espagnoles ont vu leurs effectifs de canards hivernants augmenter considérablement (+6 et +12%, alors qu'avant la MAE les tendances étaient négatives).

CHAPITRE III. BÉNÉFICES AGRONOMIQUES POTENTIELS DE LA MISE EN EAU HIVERNALE DES RIZIÈRES ET DE L'ATTRACTION DES CANARDS DANS CES DERNIÈRES

III.1 Contexte général

Le **Chapitre III** traite des bénéfices agronomiques que pourraient apporter aux agriculteurs par l'inondation hivernale des rizières et l'attraction des canards dans ces dernières aux agriculteurs. Il aborde, à travers des tests expérimentaux, les principaux problèmes agronomiques que doivent affronter les riziculteurs: la gestion des adventices (services de régulation) et celle de la paille (services de régulation).

Ces avantages agronomiques potentiels ont été résumés par Anders et al. (2008) pour les États-Unis, puis discutés en parallèle des bénéfices agronomiques de l'élevage de canards dans les systèmes d'agriculture intégrée « riz-canard » dans le Tableau 2 de l'**Article 1** (**Chapitre I**). Des études empiriques et expérimentales antérieures ont montré que les canards

peuvent apporter des avantages agronomiques aux riziculteurs, mais cela n'a qu'à une seule reprise en Europe (Navedo et al., 2015). Nous avons donc évalué expérimentalement l'effet de l'inondation hivernale des rizières sur la détérioration du riz et des graines d'adventices, ainsi que l'effet des canards hivernants et des canards d'élevage sur la banque de graines et sur les chaumes après un hiver.

III.2 Résultats clés

Les études présentées dans les articles de ce chapitre fournissent de nouveaux résultats démontrant que l'inondation hivernale des rizières et l'attraction des canards dans celles-ci peuvent bénéficier aux agriculteurs par le biais d'une augmentation de la décomposition de la paille, mais ne permettent pas forcément une réduction significative de la banque de graines d'adventices :

1/ L'inondation hivernale ne favorise la dégradation que de certaines graines (Article 4).

La masse des graines décline clairement au cours de l'hiver (-38,4% en moyenne), particulièrement en condition inondée, avec des taux qui différent d'une espèce à l'autre (voir aussi Nelms et Twedt, 1996; Foster et al., 2010; Collins et al., 2015). Les graines de riz cultivé et de riz crodo ont perdu significativement plus de masse au cours de l'hiver en condition inondée qu'en condition sèche: le riz cultivé a perdu en moyenne 46,2% de sa masse en condition sèche, contre 62,3% en condition inondée. Les chiffres correspondants pour le riz crodo étaient 26,6% et 45,3%. Pour les autres espèces (*Echinochloa crus-galli*, *Bolboshoenus maritimus*), aucun effet de l'inondation sur la perte de masse des graines n'a été détecté.

La viabilité des graines a généralement diminué au fil du temps (-43,1% en moyenne) mais l'amplitude de cette diminution n'a été significativement plus élevée en condition inondée que pour le riz cultivé. La viabilité moyenne du riz cultivé a diminué de 99,0% au début de l'hiver à 54,2% en fin de saison en condition sèche, contre 13,0% en condition inondée. Pour les autres espèces de graines, aucun effet de l'inondation sur la viabilité n'a été détecté.

Nous avons également considéré le contenu énergique des graines dans le but d'évaluer les changements de leur qualité nutritive pour les canards. Les riziculteurs pourraient également être intéressés par le contenu énergique des graines s'il existe un seuil en-dessous duquel les graines perdent leur capacité à germer. Nous avons observé que la densité d'énergie (kJ/g) demeure relativement constante au cours de l'hiver, montrant en fait une très légère augmentation, en particulier en condition inondée: +3,75% au cours de l'hiver. La quantité totale d'énergie disponible pour les canards à partir d'un échantillon de graines donné diminue donc au cours de la saison, essentiellement en raison de la perte de masse car elle n'est pas compensée par la faible concentration de l'énergie. Cette perte d'énergie brute au cours de l'hiver était relativement similaire en condition inondée ou sèche pour la plupart des graines. La seule exception est le riz crodo, dont la perte d'énergie brute était de 42,4% en condition inondée, contre seulement 26,2% en condition sèche.

En résumé, nous n'avons pas constaté que l'inondation des rizières en hiver pouvait être une pratique bénéfique pour les agriculteurs en terme de réduction de la viabilité de la banque de graines à la fin de l'hiver, contrairement à des études antérieures (Street et Bollich, 2003; Manley et al., 2005; Anders et al., 2008; Fogliatto et al., 2010; Baek et Chung, 2012).

Cependant, il reste à établir (en particulier pour le riz crodo) si les graines germeraient et les plantules croîtraient de manière similaire après inondation par rapport au traitement à sec, en étudiant les taux de germination et la biomasse des plants d'adventices le printemps suivant (Manley et al., 2005). Pour les canards, nos résultats suggèrent que la quantité et non la qualité des ressources en graines diminue au cours de l'hiver.

2/ Les canards n'ont pas d'effet significatif sur la banque de graines et ceci peut être expliqué par la répartition des graines (Article 5).

Nous avons testé, sur la banque de graines d'une rizière inondée, l'effet de canards se nourrissant pendant tout un hiver à trois densités: 5 canards.ha^{-1} (densité historique de canards sauvages), 23 canards.ha^{-1} (densité actuelle de canards sauvages) et 300 canards.ha^{-1} (densité en système intégré « riz-canard »). Le pâturage saisonnier sur une surface donnée était simulé par une charge instantanée élevée dans de petits enclos expérimentaux.

Les canards n'ont pas eu d'effet significatif sur la banque de graines. Par rapport à la situation initiale, les canards n'ont diminué le nombre moyen de graines par échantillon que de 3% seulement, à la plus forte densité d'oiseaux, et la masse des graines d'environ 21%, mais ceci n'était pas significatif. L'absence d'effets significatifs des canards sur les semences peut s'expliquer par la répartition agrégative des graines au sein de la rizière; ce qui entraîne un nombre très variable de graines par échantillon.

3/ Les canard réduisent de manière significative les chaumes et contribuent à leur immersion, ce qui peut augmenter la décomposition de la paille (Article 5).

Deux études californiennes ont précédemment observé par des tests expérimentaux que le piétinement des canards a un effet mécanique direct sur la paille, entraînant une intensification des contacts entre celle-ci et le sol, donc une plus grande accessibilité de la paille à la flore microbienne (Bird et al., 2000; Van Groenigen et al., 2003). Les canards contribuaient à réduire les concentrations de lignine et d'azote dans le résidu de surface, augmentant la décomposition de la paille de riz, la disponibilité en azote du sol et l'incorporation de la paille dans le sol. Avec de fortes densités de canards, la diminution de la masse de la paille résiduelle de surface pouvait atteindre 76% (Bird et al., 2000). Van Groenigen et al. (2003) ont également observé que la réduction de la biomasse de paille dans les champs inondés était plus de deux fois plus grande en présence de canards.

Nos tests ont montré que les canards réduisent de manière significative le nombre de chaumes de paille dressées et que cette réduction augmente avec la densité de canards: -27% pour 5 canards.ha^{-1}, -52% pour 23 canards.ha^{-1}, -91% pour 300 canards.ha^{-1}. L'attraction des canards dans les rizières inondées permettrait la diminution du nombre de chaumes debout et donc une augmentation de la décomposition de la paille par l'action conjuguée de l'eau et du piétinement des canards.

IV. DISCUSSION

IV.1 Un changement des pratiques agricoles en interculture pourrait-il être bénéfique pour les canards hivernants et les riziculteurs?

Afin de déterminer s'il existe **des pratiques inter-culturales « gagnant-gagnant » pour les riziculteurs et pour la conservation des canards hivernants dans les zones de production intensive de riz en Europe et plus particulièrement en Camargue** (France), nous nous sommes appuyés sur une variété d'approches, notamment une revue bibliographique (**Chapitre I**, **Article 1**), des études empiriques (**Chapitre II**, **Articles 2 et 3**) et expérimentales (**Chapitre III**, **Articles 4 et 5**) dans le cadre conceptuel général de la théorie de l'approvisionnement optimal, de l'agro-écologie et des services écosystémiques.

L'analyse de la littérature scientifique nous a permis d'identifier l'inondation hivernale des rizières comme une gestion de l'habitat offrant des avantages pour les canards grâce à l'utilisation directe des champs en chaumes. Du point de vue des agriculteurs, elle augmente la décomposition de la paille et diminue la viabilité des graines d'adventices par l'action conjuguée de l'eau et du piétinement des canards (**Article 1**). Les études mises en œuvre au cours de cette thèse confirment que des avantages similaires peuvent être attendus en Europe. Une corrélation positive entre la superficie en rizières inondées et le nombre de canards hivernants par site a été démontrée à l'échelle d'une aire globale d'hivernage (**Article 2**). Grâce à l'étude des processus en jeu à une échelle plus locale, en Camargue, nous avons conclu que toute mise en eau des rizières non-labourées serait une gestion appropriée pour les canards hivernants, leur permettant d'accéder au stock abondant de graines (**Article 3**). En retour, les riziculteurs peuvent attendre une participation des canards attirés sur les rizières au processus de décomposition de la paille (**Article 5**). Sur la base de ces résultats écologiques et agronomiques, nous concluons que l'inondation hivernale devrait être encouragée pour les canards en Camargue et partout ailleurs où sa mise en place serait techniquement possible. La mesure agri-environnementale « inondation hivernale des rizières » en Espagne a prouvé son efficacité, en se traduisant par une amélioration des tendances d'évolution des effectifs locaux de canards (**Article 2**).

Bien que les résultats de ce projet de recherche soient clairs et concordants d'une étude à l'autre, cette étude présente néanmoins ses propres limites.

La revue de la littérature n'a couvert que 14 des 27 critères méthodologiques définissant une revue bibliographique systématique selon la définition de Roberts et al. (2006) (**Article 1**). Parmi les critères non respectés figurent l'exécution d'une méta-analyse ou d'une analyse de sensibilité. Plusieurs de ces limitations sont dues aux sources de la littérature elles-mêmes, qui souvent ne fournissaient que des informations quantitatives et/ou difficiles à comparer entre elles.

Les liens possibles entre l'inondation hivernale des rizières et l'abondance régionale des canards ont été évalués dans cinq paysages d'Europe occidentale. Ces zones étaient très contrastées en termes de superficies couvertes par des zones humides naturelles par rapport à celles en rizières, et en terme d'inondation hivernale des rizières. Ces différences massives de paysages peuvent conduire à surestimer l'impact potentiel de l'inondation hivernale sur les effectifs de canards dans des paysages « moyens ». Cependant, les résultats de cette étude de corrélation sont soutenus par le test de l'efficacité de la mesure agri-environnementale

« inondation hivernale des rizières » mise en place en Espagne, qui a effectivement conduit à des changements positifs dans les tendances démographiques des canards (**Article 2**).

Il n'a pas été possible d'obtenir un échantillonnage réellement aléatoire des diverses pratiques en interculture sur les 50 parcelles échantillonnées au sein des 9 exploitations agricoles de Camargue étudiées (**Article 3**). En effet, la plupart des agriculteurs n'ont pas accepté de modifier profondément leurs pratiques pour le projet, sans soutien financier.

Les comptages nocturnes avec l'amplificateur de lumière ont fourni des informations sur la fréquentation des rizières par les canards (**Article 3**) mais ne renseignent pas sur les préférences ou la sélection de certains habitats, puisque seules les rizières étaient étudiées. D'autres études sur l'alimentation et la disponibilité des ressources dans les autres habitats d'alimentation (zones humides naturelles ainsi que marais agrainés), conduites avec des équipements de télémétrie type GPS aideraient à améliorer notre compréhension des mouvements et des préférences des canards au sein de l'ensemble des habitats d'alimentation disponibles. Concernant les comptages nocturnes de canards, malgré les potentielles erreurs d'estimation, doubles comptages ou détectabilité imparfaite, les résultats ont été très explicites puisque la densité nocturne de canards dans les rizières inondées était parmi les plus élevées jamais enregistrées en Camargue (24 canards/ha, quand les moyennes historiques maximales variaient entre 5 et 15 canards/ha: Pirot, 1981; Mesléard et al., 1995). Au contraire, les champs secs étaient pratiquement dépourvus de canards la nuit (**Article 3**). Bien que la tendance soit claire, la précision des mesures pourrait être améliorée en corrigeant notamment par la détectabilité (Defos du Rau, 2003).

Les deux études expérimentales ont été mises en place afin d'isoler certains processus liés aux bénéfices agronomiques potentiels pour les agriculteurs en s'affranchissant de possibles facteurs confondants qui auraient été rencontrés sur le terrain. Les processus en jeu sont clairement identifiés et les différents résultats sont à la fois cohérents et convaincants (**Articles 4 et 5**). Néanmoins, il ne faut pas oublier la situation artificielle des expériences. Par exemple, les conditions climatiques à l'intérieur de la serre peuvent avoir été différentes de celles dans les champs, ce qui pourrait avoir affecté les taux de dégradation des graines (**Article 4**). Pour aller au bout de la logique de l'expérience sous serre, celle-ci pourrait être étendue en incluant les phases de germination et d'émergence des plantules. La biomasse des plantules pourrait également être mesurée en plein champ, afin d'évaluer si l'inondation hivernale des rizières pourrait être un moyen de contrôle biologique des adventices au-delà du stade de fin d'hiver. Le test expérimental avec les canards devait également être mené sur une période de temps limitée pour des contraintes évidentes liées à l'utilisation d'oiseaux dans des enclos. Nous avons simulé la présence d'une faible densité de canards pendant tout un hiver à l'aide de nombreux oiseaux dans un petit enclos sur une courte période de temps. Cela nous a empêché de mesurer à proprement parler la décomposition de la paille sur plusieurs mois, et seule la submersion des chaumes a été considérée (**Article 5**). Ces études, qui fournissent déjà des résultats intéressants, pourraient être améliorées par des expériences complémentaires.

IV.2 Qu'implique une gestion particulière des rizières en interculture pour la conservation des canards?

Les canards de surface hivernants dans les régions rizicoles d'Europe n'appartiennent pas à des populations menacées (IUCN, 2014) ; leurs effectifs globaux sont en augmentation (canard chipeau, sarcelle d'hiver, colvert), stables (siffleur, souchet) ou fluctuants (pilet) (Szabolcs et al., 2015). Quoi qu'il en soit, ces oiseaux fournissent des services écosystémiques

culturels importants, en particulier à travers leur valeur esthétique et la chasse (Mathevet, 2000), et sont parmi les espèces d'oiseaux d'eau reconnus pour être particulièrement sensibles aux changements dans l'utilisation des terres à l'échelle locale (ex, Duncan et al., 1999; Mathevet et Tamisier, 2002). La Camargue est le premier quartier d'hivernage français pour plusieurs espèces de canards et l'une des zones les plus importantes à l'échelle des voies de migration européenne (Critical Site Network Tool, 2015). Il était donc pertinent d'évaluer comment les changements dans la gestion de l'habitat camarguais peuvent influer les processus de migration de ces oiseaux et la dynamique de leurs populations, à la fois localement et à l'échelle des voies de migration (voir aussi Rendón et al., 2008 et Toral et Figuerola, 2010). Nos résultats suggèrent effectivement que la gestion de ces espaces rizicoles pourrait avoir un impact important sur les populations de canards (**Article 2**).

Etant donné qu'en Camargue: 1) la disponibilité des sites d'alimentation nocturnes a été identifiée comme un facteur limitant pour les canards (Brochet et al., 2009), 2) que ces oiseaux sont relativement fidèles à leur remise diurne (Guillemain et al., 2009; 2010) et volent sur de courtes distances pour leur alimentation nocturne (Guillemain et al., 2008), et 3) que de nombreuses aires d'alimentation potentielles existent dans les rizières moissonnées mais ne sont pas utilisées par les canards car gardées en chaumes sèches, nous pouvons supposer que l'inondation hivernale des rizières pourrait immédiatement profiter aux canards hivernants. Grâce à une plus grande attractivité de sites d'hivernage gérés de la sorte, nous pouvons émettre l'hypothèse que des changements de leur temps de résidence (Delta de l'Ebre: Ferrer 1986 versus Oltra et al., 2001; Camargue pour les sarcelles: **Guillemain et al., 2015a, Annexe I.2**) et des changements de distribution (Californie, vallée de Sacramento, Fleskes et al., 2005) pourraient être observés. La mise à disposition de champs inondés pourrait non seulement se traduire par une utilisation ponctuelle ou saisonnière de ces champs par les canards pendant un hiver donné, mais une tradition d'hivernage forte pourrait également se développer dans ces habitats (**Guillemain et al., 2015a, Annexe I.2**) et donc se traduire par une amélioration de la dynamique des populations plutôt que la simple satisfaction temporaire des besoins énergétiques des oiseaux. En effet les tendances démographiques ont augmenté après la mise en place de la MAE « inondation hivernale des rizières » en Espagne (**Article 2**).

Nous pouvons donc émettre l'hypothèse que la mise en œuvre de façon extensive de l'inondation hivernale des rizières en Camargue influencerait les mouvements et la distribution locale des canards et aurait un effet positif plus large sur leurs populations. Cependant, nous ignorons largement ce qui se passerait simultanément dans les autres habitats d'alimentation naturels (zones humides peu profondes ou marais de chasse). De plus, à plus grande échelle le changement climatique provoque le déplacement de certaines espèces de canards vers le nord-est (Gunnarsson et al., 2012; Lehikoinen et al., 2013; Dalby, 2013; Elmberg et al., 2014, **Guillemain et al., 2015a, Guillemain et al., 2015b, Annexes I.2 et I.3**). Nous ignorons dans quelle mesure l'inondation hivernale des rizières en Camargue, quartier d'hiver situé très au sud de l'aire de répartition de beaucoup d'espèces d'Anatidés, pourrait compenser les conséquences du changement climatique.

Par conséquent, au-delà d'une amélioration générale des conditions locales de l'habitat pour les canards, il est difficile de prédire à partir d'études empiriques et expérimentales telles que celles présentées dans cette thèse quelles pourraient être localement les conséquences de changements massifs des pratiques inter-culturales. Cependant, ces études peuvent déjà fournir certains des paramètres nécessaires à un exercice de modélisation. Ceci constitue un

projet initié au cours de cette thèse et que nous développerons d'avantage dans un futur proche.

L'objectif est d'utiliser la modélisation prédictive afin d'évaluer les conséquences probables de l'inondation hivernale des rizières dans la mosaïque paysagère camarguaise sur certaines variables individuelles des canards de surface telles que leur condition physique, leur survie, leurs modes d'utilisation de l'habitat ou leur budget temps. Pour atteindre cet objectif nous avons mis en place une collaboration avec le professeur John Eadie et son équipe à l'Université de Davis (Californie), qui ont développé un modèle multi-agents spatialement explicite appelé SWAMP (Spatially-explicit Waterbird Agent-based Modeling Program: Miller et al., 2014). Ce modèle est relativement similaire au modèle européen MORPH (Stillman, 2008). La version la plus récente (jusqu'ici non publiée) de SWAMP est parfaitement adaptée à notre question, car elle permet l'intégration par système d'information géografique d'un paysage agricole. Le programme simule ensuite les mouvements de canards entre leurs remises diurnes et les gagnages nocturnes. En outre, il est beaucoup plus précis que les modèles énergétiques (ex : TRUEMET: Petrie et al., 2014) car il considère l'hétérogénéité des comportements individuels et des conditions corporelles (détails dans la Discussion en anglais).

Grâce à une bourse à la mobilité internationale de l'Ecole Doctorale de l'Université de Montpellier, j'ai pu réaliser un séjour de trois semaines en février 2015 dans le laboratoire du Professeur J. Eadie. Cette période a été consacrée à la prise en main du modèle SWAMP, à la définition de scénarios potentiels de gestion en Camargue, à des premiers tests de simulation et à l'identification des modifications nécessaires à une utilisation complète en Camargue (modifications de code et paramètres manquants). Une fois adaptés et paramétrés, l'application de SWAMP au cas camarguais apportera des arguments solides aux gestionnaires et aux politiciens à l'horizon de la PAC 2017. Les agriculteurs et les décideurs de Camargue sont déjà familiarisés à l'exercice de simulation pour collaborer avec les scientifiques (ex : logiciel Mar O Sel, http://www.mar-o-sel.net, Lefebvre et al., 2015). Nous croyons que la mise à disposition d'un modèle multi-agents puissant aiderait les riziculteurs et les gestionnaires à tenir compte des conséquences des pratiques de gestion des rizières en interculture, et à adopter celles que nous avons démontrées dans cette thèse être les plus bénéfiques à la conservation des canards.

IV.3 Qu'implique une gestion particulière des rizières en interculture pour les riziculteurs, pour la société et pour les décideurs?

Nous avons effectué une analyse coûts-bénéfices prenant en compte tous les coûts marchands et non-marchands (agronomiques et environnementaux) afin d'évaluer si l'inondation hivernale des rizières en France serait économiquement réaliste pour l'agriculteur compte tenu des contraintes économiques liées notamment aux coûts du pompage de l'eau. Pour la société nous avons aussi considéré les émissions de gaz à effet de serre ainsi que les services culturels apportés par les rizières inondées (écotourisme, chasse) (**Article 6, Annexe I.1**).

Pour résumer brièvement les résultats de cette analyse, la pratique du brûlage-labour traditionnel tolérée en Camargue atteint à peine l'équilibre financier pour l'agriculteur et n'est pas économiquement acceptable pour la société (bénéfices sur coûts <1), principalement en raison des coûts liés aux gaz à effet de serre et à l'absence d'avantages écosystémiques associés à l'inondation. Les autres itinéraires techniques étaient tous économiquement

réalistes à la fois pour l'agriculteur et pour la société (bénéfices sur coûts >1). La récolte du riz dans les champs inondés apparaît comme quatre fois plus rentable pour les agriculteurs et plus de huit fois plus pour la société camarguaise que le brûlage-labour traditionnel (ratio bénéfices/coûts pour les agriculteurs 4,15 vs 1,02, pour la société 6,67 vs 0,78). L'analyse de sensibilité a confirmé la robustesse des résultats. L'inondation hivernale est donc économiquement réaliste pour les agriculteurs et fortement bénéfique pour l'environnement et mérite d'être encouragée.

La production de riz en Europe ne représente que 0,5% de la production mondiale (FAOSTAT, 2012). La production française représente 4% du total européen et a une faible productivité et compétitivité en raison de conditions climatiques relativement inappropriées et un accès aux pesticides plus réduit que les plus grandes et puissantes productions de riz espagnole et italienne (C. Thomas, com. pers.). En conséquence, la production de riz française fluctue fortement en fonction des incitations financières nationales et des prix du marché mondial (entre 32 000 ha en 1960 et 4 000 ha en 1981) qui induisent des changements rapides de l'activité économique, des stratégies des exploitations agricoles et donc du paysage camarguais (Picon, 2008) (détails dans la Discussion en anglais). Le riz est actuellement la culture la plus répandue dans le delta (61,5% des surfaces cultivées en 2011, PNRC, 2013a). La réforme de la PAC 2015 a toutefois déjà provoqué de nouveaux changements dans le paysage. Avec la suppression du soutien financier spécifique à la culture de la riziculture (aides découplées), des changements dans les cultures camarguaises ont déjà été observés, avec une réduction de 28% de la superficie de riz entre 2012 et 2014, et le remplacement de ces dernières par des cultures sèches comme le blé ou les cultures maraichères.

Dans le cadre de la réforme de la PAC 2015, une série de mesures agri-environnementales et climatiques associées à la production de riz a été introduite pour compenser le manque à gagner d'environ 250 €/ha par rapport à la situation antérieure. A titre comparatif, l'inondation hivernale des rizières dans les sites Ramsar espagnols est soutenue à hauteur de 60 €/ha. Fournir des incitations financières aux riziculteurs français pour inonder les champs, comme en Espagne, peut être nécessaire pour leur permettre de réaliser les avantages (y compris agronomiques) de cette pratique. Les ratios bénéfices sur coûts de l'inondation hivernale pour la société sont si élevés qu'ils resteraient bien au-dessus de 1 (donc toujours économiquement bénéfiques), même si une incitation financière était versée aux agriculteurs.

L'inondation des rizières ne peut cependant être considérée comme une panacée, car cette pratique pourrait être en conflit avec les programmes de réduction des émissions de gaz à effet de serre (http://www.greenrice.eu/about-us/, http : //www.sostrice.eu/en/), sauf si cette mesure est prise comme alternative à l'écobuage de la paille de riz (Couderc, 2013). Elle peut également aller à l'encontre des efforts pour réduire la consommation d'eau (http://www.greenrice.eu/about-us/) ou pour promouvoir l'agriculture biologique (Mouret, 2013) car l'inondation hivernale des rizières implique des années successives de production de riz, tandis que la culture biologique du riz repose souvent sur une rotation régulière avec d'autres cultures. Cependant, cette pratique est en conformité avec la plupart des autres programmes des organisations européennes ou françaises de production de riz : la recherche d'alternatives à l'écobuage de la paille de riz (Monier et al., 2009 en France; ECORICE-LIFE04 ENV/ES/000184, Albufera de Valencia), la réduction des pesticides (Plan national Ecophyto 2018 en France), et la réduction de la salinité du sol (sélection de variétés de riz tolérantes au sel, France AgriMer, NEURICE). Dans ce contexte, la "crise" actuelle du riz appelle à de nouvelles recherches et la gestion alternative par inondation hivernale proposée

ici pourrait être considérée pour les avantages agronomiques et environnementaux qu'elle peut apporter, ouvrant ainsi la voie à une nouvelle source de revenu pour les producteurs de riz dans une période difficile pour eux.

IV.4 CONCLUSION: Ce que ces résultats impliquent - et n'impliquent pas - pour la gestion des terres de Camargue

Ce travail de thèse a porté exclusivement sur la communauté de canards de surface utilisant des rizières pendant la période interculturale. Nous sommes conscients que les canards ne constituent pas l'ensemble de la communauté d'oiseaux qui utilisent ces habitats, et que la période post-récolte n'évalue pas l'importance de la production de riz pour les oiseaux en général (Tourenq, 2000; Toral, 2011). Au cours de la période interculturale, les rizières sont également importantes pour d'autres oiseaux d'eau tels que la barge à queue noire *Limosa limosa* (Lourenço et Piersma, 2008; Lourenço et al., 2010), les bécassines *Gallinago gallinago* (Beck et al., 1999), la cigogne blanche *Ciconia ciconia* ou la spatule blanche *Platalea leucorodia* (Marti et del Moral, 2003). Ces espèces ne seraient pas nécessairement favorisées par les mêmes niveaux d'eau ou pratiques post-récolte que les canards (Toral et al., 2011). L'inondation hivernale des rizières elle-même peut être défavorable pour d'autres espèces de rapaces, fringilles ou colombidés, qui utilisent essentiellement les rizières sèches (Elphick, 2004). En Camargue, un important hivernage de grues cendrées (*Grus grus*) se développe ainsi depuis quelques années dans les rizières non inondées.

Des recherches antérieures en Camargue, menées à la fois sur la période de culture et d'interculture, mais limitées à des comptages diurnes, ont conclu que la diversité des oiseaux était plus faible dans les rizières (31 espèces) que dans les marais naturels (59 espèces) (Tourenq et al., 2001). Nos résultats montrent que les zones humides naturelles et les rizières inondées sont complémentaires. Nous ne négligeons pas que la riziculture, n'est pas nécessairement la meilleure option pour la biodiversité en général (Tamisier et Grillas, 1994), mais notre objectif ici était de rétablir la fonction d'habitat d'alimentation pour les canards que peuvent jouer les rizières. Il est important de noter que nous ne préconisons pas la conversion de marais naturels en rizières, seulement un changement dans la gestion des champs existants pour les rendre accessibles aux canards pour leur alimentation.

L'option mutuellement bénéfique que pourrait représenter l'inondation hivernale des rizières pour les canards et les agriculteurs ouvre le dialogue et appelle à la collaboration scientifique entre écologues et agronomes. Les agronomes ont commencé à travailler sur de nouvelles stratégies agricoles en Camargue (ex: Jaek, 2010; Delmotte, 2010). Cependant, ces études considèrent surtout la promotion de l'agriculture biologique localement. La question de comment améliorer la riziculture conventionnelle, qui domine actuellement le paysage, en intégrant des approches agronomiques et écologiques a au contraire reçu une attention très limitée jusqu'ici. L'introduction à grande échelle de l'inondation hivernale pourrait être un bon moyen de tirer le meilleur de la connaissance récente obtenue dans ces deux disciplines. Dans le contexte des problèmes actuels de production de riz, provoquant une baisse de la superficie rizicole en Camargue, l'inondation hivernale pourrait aussi ouvrir la voie à de nouveaux revenus pour les producteurs de riz et contribuer à surmonter la crise.

La réforme de la Politique Agricole Commune 2015 a entraîné récemment une réduction de la surface rizicole d'un tiers, induisant deux changements majeurs dans le paysage: l'augmentation des friches agricoles et le développement de cultures sèches. L'augmentation de la superficie en friches avait déjà été remarquée en 2011 lors de l'étude de l'occupation du sol en Camargue (PNRC, 2013a), et il est attendu qu'elles continuent à s'étendre, principalement sur les terres salées de basse altitude. Ces zones peuvent représenter une bonne occasion pour des projets de restauration des zones humides. Comme pour la zone de production rizicole de Doñana dans le delta du Guadalquivir, la restauration d'anciennes rizières en marais (Mesléard et al., 1995; Muller, 2013) pourrait compléter le maintien de rizières inondées en hiver. Ceci représentait une stratégie plus écologique que la transformation de ces rizières abandonnées en champs de coton (Doñana), de tomates (Camargue) ou en fermes solaires (Toral, 2011).

Au début de cette thèse, nous nous demandions si une « intensification durable » serait possible dans les rizières européennes. Nous avons pu démontrer que des scénarios agricoles "gagnant-gagnant" pour les riziculteurs et la conservation des canards sont envisageables au sein de ces zones de production intensive, notamment en France. La dernière étape du cadre conceptuel de gestion adaptative est le transfert de connaissances. Une telle communication est nécessaire pour combler le fossé entre les chercheurs, les gestionnaires (y compris les agriculteurs) et les décideurs, afin de confronter leurs visions communes ou parfois divergentes du paysage (Vuillot, 2015), en vue de faciliter une mise en œuvre pratique. Nous avons initié ce transfert auprès de tels publics, tant à l'échelle camarguaise qu'européenne (**Annexe III**). Les résultats de nos recherches ont été bien accueillis par les agriculteurs, les chasseurs, les gestionnaires d'espaces naturels et les personnes en charge de la conservation des zones humides et des oiseaux d'eau. En raison de la nature itérative du cycle de gestion adaptative, cette étape finale de transfert et d'apprentissage est souvent aussi un apport important pour les prochaines étapes du cycle du projet. Nous espérons que les résultats de cette thèse vont contribuer à augmenter la valeur de conservation des rizières, tout en maintenant la viabilité économique d'une l'agriculture durable et productive.

INTRODUCTION

"Flowers" Made with duck feathers by Samuel Lei, California

I. Agroecosystems: threats and opportunities

I.1 Agroecosystems as integrated elements of the landscape

Agriculture expansion and intensification are recognized as two of the most important global threats to biodiversity (Donald et al., 2006), causing generalized disruptions of ecosystem functions. Continued human population growth induces an increased demand for food, which is projected to double by 2050 (Tilman et al., 2001), and more recently for biofuel (Miyake et al., 2012). This situation causes the rise of two major threats: conversion of pristine habitats into crops in developing countries (mostly in South America and Western Africa), and intensification of existing agricultural systems in more developed nations (Donald et al., 2006). **In the short to medium term, urgent measures thus need to be taken to ensure food production sustainability.**

The dominant late twentieth century model of land use clearly segregated areas of agricultural production from areas managed to conserve biodiversity. Cultivated systems are currently the dominant landscape, accounting for 24% of the Earth's terrestrial surface (MEA, 2005). In Europe they represent one of the most widespread forms of land use, over 45% of the enlarged European Union (EU 27) area (Henle et al., 2008). Up to 50% of the globe's agricultural lands and 60% of ecosystem services (i.e. the benefits people obtain from ecosystems, MEA, 2005) are now affected by some degree of degradation themselves (MEA, 2005). **Given the recognised ecological role of functional biodiversity for crop production** (Altieri, 1999), **agricultural landscapes have to be managed to promote biodiversity, which often can induce positive effects on agricultural production and livelihoods** (Scherr and McNeely, 2008).

According to the Millennium Ecosystem Assessment, ecosystem services can be classified in four categories: *provisioning services* which are products obtained from ecosystems, such as food, fibres, fuel, genetic resources, medicine and water; *supporting services,* necessary for primary production such as soil formation, photosynthesis, nutrient and water cycling; *regulating services* which correspond to benefits obtained from the regulation of ecosystem processes, such as pollination, pest regulation, air quality, climate, flood, erosion regulation; and *cultural services* such as recreational, spiritual, and other nonmaterial benefits (MEA, 2005).

According to Swift et al. (2004) agroecosystems are: "*(natural) ecosystems that have been deliberately simplified by people for the purpose of production of specific goods of value to humans*". Provisioning ecosystem services (the crop production) have historically been considered as the highest priority service provided by agricultural landscapes, but these landscapes are seldom viewed as potential producers of supporting, regulating or cultural ecosystem services (Power, 2010). In parallel, agricultural ecosystems are often considered as a source of numerous disservices, including the destruction of natural ecosystem services. However, agroecosystems largely require natural ecosystem services for their own maintenance (e.g. pollination, pest control) (Power, 2010). **How agroecosystems are integrated and interact with natural features or habitats in the landscape, and whether agroecosystems may or may not themselves provide ecosystem services other than crop yield largely depends on how they are managed** (Altieri, 1999; Swift et al., 2004; Power, 2010, see also the importance of farm management on the ecosystem service flow: **Figure 1**).

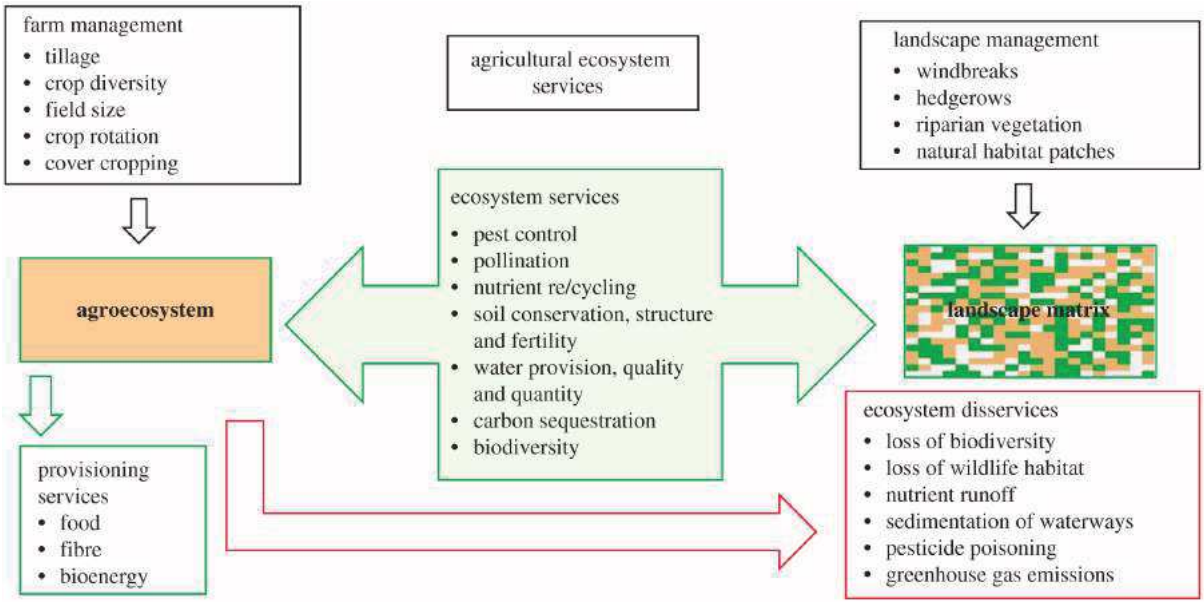

Figure 1. Impacts of farm and landscape management on the flow of ecosystem services and disservices to and from agroecosystems (reproduced from Power, 2010).

From the agronomic point of view, functional biodiversity in crop fields can be promoted through **agroecology**, a discipline taking into account the effects of the integration of plant and animal biodiversity to enhance complex interactions, hence simulating natural ecosystem complexity and functions (e.g. Agroforestry or ''Integrated Rice Duck Farming'' in Asia). Similarly, **integrated weed, pest and disease management** aims at reducing such hurdles to cultivation by considering the biotic interactions among multiple components of the pest complex present in the ecosystem (Shennan et al., 2008). This approach considers that a better integration of ecological mechanisms such as disturbance or interaction complexity, emerging from the study of natural ecosystems, can provide insights into how biotic interactions may determine agroecosystem function (e.g. Ormerod et al., 2003). Currently, research studies aim at filling the gap between agronomy and ecology by promoting **management procedures that encourage beneficial biotic interactions within agroecosystems, and minimize undesired ones** (Shennan et al., 2008). **Ecologically-based management** concepts are developed at larger scales, that take into consideration the whole system and not only one field or one production, e.g. the **"Ecoagriculture landscape"** (Scherr and McNeely, 2008).

In order to satisfy growing food needs, and to integrate biodiversity components into agriculture, the concept of **ecological intensification** inducing **sustainable intensification** has been proposed (Bommarco et al., 2013). This implies the protection of ecosystem services for environmentally sustainable agriculture and the increase of food production from existing agricultural lands without further environmental damage. This is a tremendous challenge for intensive agricultural areas, which has been identified as one of the main and urgent conservation issues for 2015 (Sutherland et al., 2015).

I.2 Relevance of the Ricefield-Duck model

Rice is **the second most widely grown cereal in the world**, covering almost one percent of the Earth surface (FAO-STAT, 2013; Lawler, 2001). This production represents a **threat for wetland** ecosystems where ricelands are implanted on converted former natural habitats (e.g. Western Africa) and where rice is intensively produced (as is the case in Europe). On the other hand, rice fields are artificial wetlands and represent 15% of the world's total wetland area (Lawler, 2001). They have been recognized by the Ramsar Convention Resolution X.31 as an **important ecosystem for *"supporting biodiversity and livelihoods as wetland systems"*** (Nagoya conference, COP 10, Dean-Speirs et al., 2010).

Rice fields are generally **inserted into a more complex landscape** of natural or semi-natural wetlands, and thus show biotic interactions with these (King et al., 2010). **Their capacity to mitigate the loss of natural wetland** habitats, or at least to **complement more natural or semi-natural wetlands** is discussed, particularly in the North Mediterranean (e.g. Fasola and Ruiz, 1996; Tourenq et al., 2001; Toral and Figuerola, 2010). In the Mediterranean region, 80 to 90% of natural wetlands have been lost (Finlayson et al., 1992), and ca. 23% of the remaining wetlands are artificial (including rice fields, salt pans or irrigation reservoirs) (Perennou et al., 2012). The importance of these agricultural wetlands for biodiversity, and more precisely for waterbird conservation, has been recognized worldwide (Czech and Parsons, 2002; Elphick et al., 2010) including in Europe (e.g. Longoni et al., 2010; Sánchez-Guzmán et al., 2007; Toral and Figuerola, 2010; Masero et al., 2010).

Birds are recognized to be **sensitive to agricultural management change, and have been widely studied** (Pain and Pienkowski, 1997; Wilson et al., 2009; Fuller, 2012). Farmland birds, in particular, have been reported to be threatened by agriculture intensification for multiple reasons (see section below), while simultaneously **providing many different ecosystem services** (Whelan et al., 2008; Weeny et al., 2011). However, most research on farmland birds has focused on passerines and other dry land birds in Europe (e.g. Pain and Pienkowski, 1997; Wilson et al., 2009). Conversely, the use of croplands and the consequences of agricultural land transformation and agricultural practices on duck populations have received more limited attention (see however e.g. Thomas, 1982, Van Eerden et al., 1996; Duncan et al., 1999). Waterfowl potentially provide a myriad of ecosystem services (Green and Elmberg, 2014), poorly explored in an agronomic perspective. The main exception concerns the potential benefit brought by waterfowl to rice farmers, but this has almost exclusively been studied in North America (e.g. Anders et al., 2008), while virtually nothing is known for such systems in Europe (except for the recent work on nutrient recycling by waterbirds in Navedo et al., 2015). One explanation to this lack of studies is that European ducks mostly use agricultural lands as nocturnal foraging grounds (Tamisier and Dehorter, 1999; Pirot, 1981; Mesléard et al., 1995), which often makes observation arduous in the field.

Currently, 24% of the waterfowl species are considered endangered (Wetlands International, 2013), compared to 19% for all bird species (Butchart et al., 2004). Green (1996) identified wetland loss as the main cause of many such declines, and Long et al. (2007) reported changes of the agricultural land - interpreted as a proxy for wetland loss - as the main threat. **Because the main European ricefield regions are often situated close to or embedded within the largest waterfowl winter quarters, appropriate management of such croplands could benefit waterfowl conservation.**

Like many other crop productions, rice cultivation intensified after the Second World War, with observed negative impacts on biodiversity (Donald, 2004). Rice intensification does represent a threat to some waterfowl species (e.g. Madagascar Pochard *Aythya innotata*, or Philippine Duck *Anas luzonica*, IUCN, 2014). On the other hand, it can simultaneously boost other threatened species (e.g. West Indian Whistling Duck *Dendrocygna arborea* in Cuba, Acosta et al., 2010, or Baikal Teal *Sibirionetta formosa* in Japan, Tajiri et al., 2014) to the extent that some can even become crop pests (White-faced Whistling Duck *Dendrocygna viduata* in Africa, Katondo, 1996, or Spot-billed Duck *Anas poecilorhyncha* in Asia, Lane, 1998). Changes in rice farming practices towards intensification may also cause declines in common waterfowl species traditionally using such habitats, calling for **waterfowl-friendly management of rice fields** (in Japan, Kasahara and Koyama, 2010). **Many waterfowl species worldwide are directly or indirectly relying on rice production areas during at least one stage of their life cycle** (Elphick et al., 2010). Like other bird species relying on agricultural ecosystems, waterfowl mostly use rice fields for foraging purposes, so whether such fields can provide suitable and accessible food resources will largely determine their potential use by ducks.

I.3 Agriculture intensification and farmland bird decline in Europe: food resources matter for seed-eating birds

In Europe, arable farming has a long history from its origins in the eastern Mediterranean 10,000 years ago, creating a tremendous variety of so-called agricultural landscapes (Stoate et al., 2001). After millennia of agricultural expansion and despite their artificial nature, a wide range of species have adapted to these extensively managed landscapes, resulting in the development of many anthropogenic species-rich agroecosystems (Kleijn et al., 2006). Among farmland ecosystems, lowlands support the largest number of bird species, nearly 120 “Species of European Conservation Concern” across Europe (Tucker, 1997). Bird populations and agricultural landscapes are therefore often tightly linked. In Europe, as much as 30% of observed variation in bird population trends can be explained by fluctuations in cereal production (Donald et al., 2001).

As a result of land intensification or abandonment, current agricultural activities are responsible for a widespread loss of biodiversity, threatening farmland birds among other taxa. In the second half of the 20th century, ecosystems changed more rapidly than at any other time in recorded human history. In fact, more land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850 (MEA, 2005). In Europe, the modern agricultural policy has its origins in the drive to increase production right after the Second World War (Pain and Pienkowski, 1997). By the advances in technology and high prices support for increased productivity, the Common Agricultural Policy (CAP) has been the driving force behind intensification and specialisation of arable farming in Europe (Donald et al., 2001). In these agroecosystems, increased use of fertilisers and pesticides, greater mechanisation, simplification of crop rotations and loss of many natural features (e.g. hedgerows) have led to a reduction in landscape diversity, soil deterioration, water pollution and disruption of food chains (Stoate et al., 2001), affecting both plant (e.g. Marshall et al., 2003) and animal populations (e.g. Wilson et al., 1999). Since the 1970s, farmland birds decreased in abundance more than any other bird community in Europe (Donald et al., 2001; 2006). A recent study showed that over the past three decades, more than 420 million birds have disappeared from the European continent, agricultural intensification being one of the main causes of this reduction (Inger et al., 2015). About a half of farmland birds are in decline or threatened in Europe (Pain and Pienkowski, 1997).

Halting such declines requires a good understanding of species habitat use and requirements through the identification of limiting factors, critical habitat needs and possible habitat management (e.g. Sutherland and Hill, 1995; for birds in Fuller, 2012). Fuller (2012) referred to **habitat use** as « *the way that an individual or population uses habitat. Similar to habitat occupancy but implies a need to specify the type of activity, e.g. nesting, roosting, foraging* », and to **habitat preference** as « *a positive association (usually of individuals in a population) with a defined habitat type, i.e. non-random distribution resulting in a disproportionately high number of individuals in certain habitat types relative to their availability* ».

A complex array of agricultural management factors might influence population changes in plants, insects and birds (**Figure 2**). Although species responds individually to each particular change in arable management, certain groups of species share common causal factors (Newton, 2004). For instance, declines of seed-eating birds have been associated primarily with a reduction of seed food resources during the non-breeding season due to weed-control, mainly through the use of broader-spectrum herbicide combinations, change from spring-sown to autumn-sown crops, associated with earlier ploughing of stubbles (Wilson et al., 1999; Moorcroft et al., 2002; Robinson and Sutherland, 2002; Marshall et al., 2003) and more recently by the use of stripper-header harvesters (Stafford et al., 2006; Fleskes et al., 2012). Ecologists are now convinced that weeds have a role within the agroecosystem in generally supporting biodiversity (Marshall et al., 2003). As a consequence, the spatial and temporal distribution of seed resources as well as seed availability is better taken into account, and the extent to which particular management might affect seeds is analysed through empirical or modelling studies (Butler et al., 2010; Evans et al., 2011; Ponce et al., 2014).

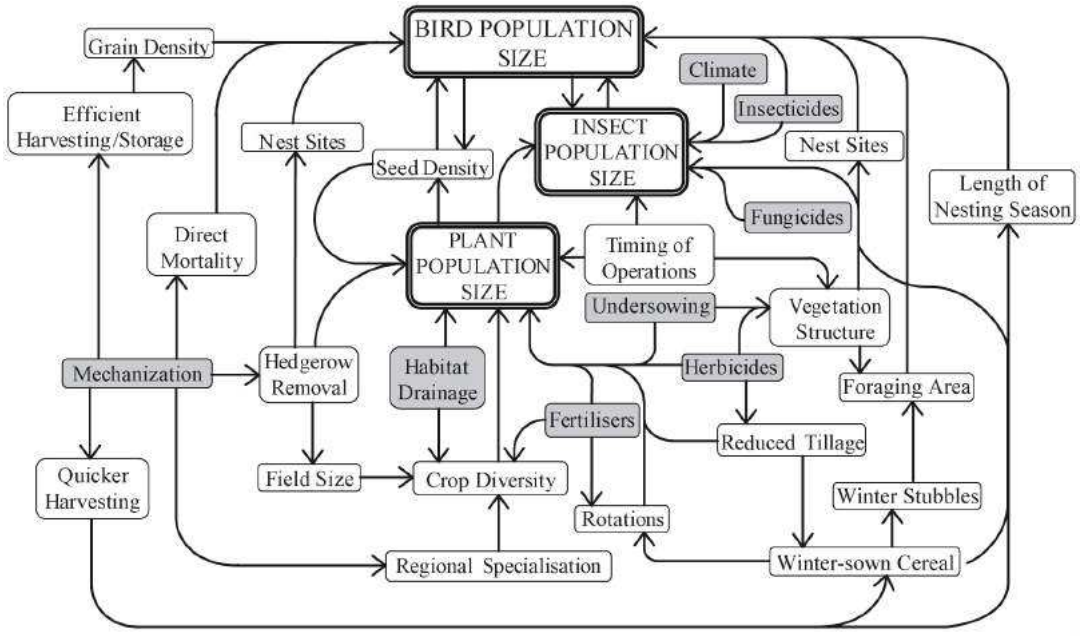

Figure 2. Changes in arable land management that might influence plant, insect and bird populations. The most relevant drivers are highlighted by shading (reproduced from Robinson and Sutherland, 2002 with kind permission from Journal of Applied Ecology).

Among the activities of organisms, acquisition of food resources is of particular importance. In fact food consumption, the necessary means to extract energy from the environment and fulfil daily energetic requirements, is a vital priority allowing survival, growth and reproduction of individuals (Stephens and Krebs, 1986). Exploitation of a resource by organisms involves a wide range of components interacting with a list of processes that constraint or favours the use of a potential habitat (**Figure 3**).

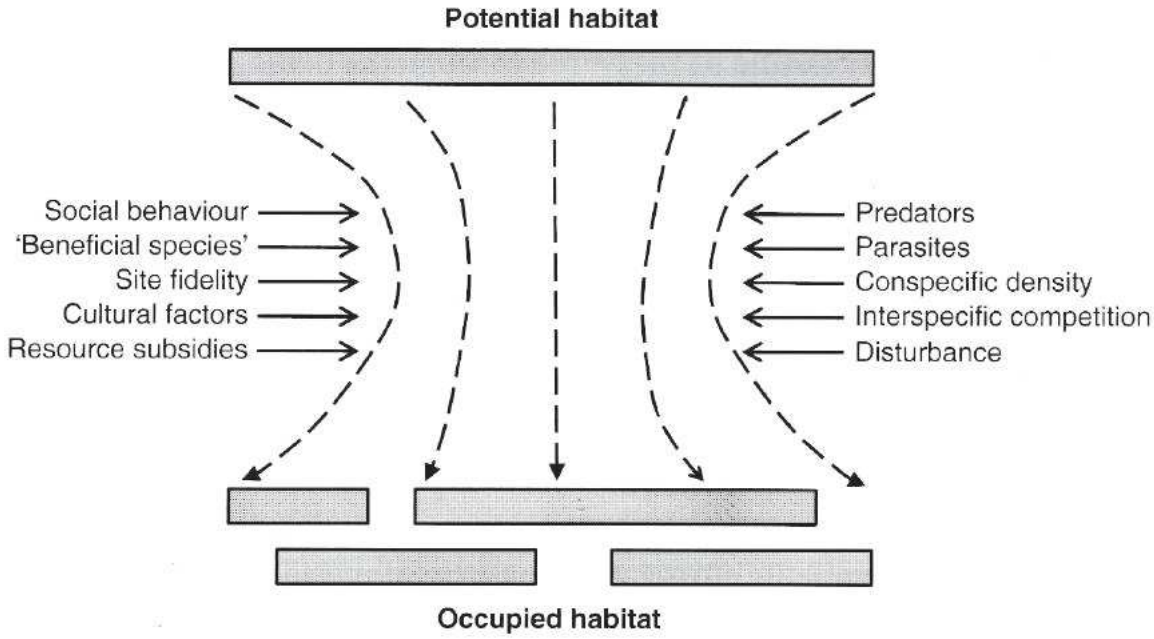

Figure 3. Processes acting to limit the distribution of individuals within certain parts of the potential habitat spectrum (wide bar at the top) (reproduced from Fuller, 2012 with kind permission from Cambridge University Press).

Consequently **the abundance and accessibility, that jointly determine the availability of food resources, act as key factors** limiting individual fitness and the size of populations in most systems (Newton, 1998).
It is important to consider that:

1) all potential food present in a habitat patch is not necessary available to an organism, as availability depends on the consumer's foraging habits and behaviour (granivores, herbivores, etc..), its morphological capacity (e.g. bill size) as well as food characteristics (size, shape, energetic content; Sutherland, 1996; e.g. for ducks, Guillemain et al., 1999).

2) food availability for a given individual may change over time and with environmental factors. Depletion is a key process influencing resource availability, since such consumptive use by foragers gradually reduces resource abundance (Sutherland, 1996). For seed banks in agroecosystems, declining resource availability can also be the product of potential seed degradation by rotting, or seed disappearance by germination as well as tillage agricultural practices making seeds inaccessible (e.g. for waterfowl, Geer et al., 2009). Because it affects food intake rate, change in seed availability may affect the distribution of the foraging birds within the habitat matrix (Sutherland, 1996).

3) apart from predation risk and competition (Guillemain et al., 2001), accessibility of available food resources depends essentially on abiotic factors, i.e. for granivorous waterbirds the water depth, the type of soil and the relative abundance and nature of plant, shell debris, and other mineral materials (Tamisier, 1971; Gurd, 2007). Another factor influencing the potential use of a given food source is the energy dissipated in locating and ingesting it (Stephens and Krebs, 1986). Under a certain threshold, resources are too scattered and require such an expenditure of energy from the organism to find them that the calories they contain are no longer sufficient to balance the foraging costs. Below this threshold, resources are considered no longer profitable. This theoretical threshold, called giving-up density (GUD), hence represents the limit in food abundance below which an organism ceases foraging (Reinecke et al., 1989). For waterfowl in post-harvest rice fields, the GUD has been estimated by Reinecke et al. (1989) and Geer et al. (2009) as ca. 50 kg/ha.

Understanding the dynamics of food resources in a habitat is important for determining its potential carrying capacity for birds and other consumers. Carrying capacity has been classically defined as the maximum number of individual-days that can be supported by the food supplies of a habitat (Goss-Custard et al., 2003). Following that definition, carrying capacity of foraging habitats for waterfowl is defined as duck-use-days (DUD's) (Prince, 1979; Reinecke et al., 1989). DUD's are the number of ducks that can survive for one day per ha. They have often been calculated as follows:

$$\text{DUD} = \frac{[\text{food available (g dry mass)} * \text{metabolizable energy (kcal/g dry mass)}]}{[\text{individual bird daily energy requirements (kcal/day)}]}$$

In overwintering migrating birds, carrying capacity has also been defined as the maximum number of individuals that can survive the non-breeding season (Goss-Custard et al., 2002). This can be estimated using spatial depletion models (SDM), in which patches of differing food density are treated separately (Goss-Custard et al., 2003; Sutherland, 1996).

Appropriate winter habitat management, sometimes including specific agricultural practices, should be regarded as an opportunity to promote carrying capacity for wintering waterfowl through increased food availability, including in riceland ecosystems (Ma et al., 2010).

I.4 From science to policy to science: implementation of Agri-environment schemes during the winter period

In the 1970s, the destructive impact of agriculture became increasingly evident, together with the need to better protect the environment and the realization that alternative agricultural practices were possible. As a result, since the mid-1980s, European governments and the European community began to embark upon the implementation of a common agri-environmental policy. Legislation about conservation of biodiversity in the EU is primarily founded on two Directives, the Birds Directive (1979) and the Habitats Directive (1992). Agri-environment schemes (AES) are considered the most important policy instruments to counteract the negative effects of modern agriculture on the environment by providing financial incentives to farmers for adopting environment-friendly practices, i.e. those in line with the Birds and Habitats Directives. Farmers contract those AES through the Common Agricultural Policy (CAP) (EC Directorate General for Agriculture and Rural Development, 2005).

Several agri-environnement schemes have been set up in the EU to maximize seed food resources in an attempt to halt the decline of seed-eating birds. For instance, game cover crops (Stoate et al. 2004), supplementary winter seed resources (Siriwardena et al., 2007) or non-inversion tillage (Cunningham et al., 2005) are applied to farmlands in the UK as agri-environment schemes. Non-inversion tillage means that farmers prepare a seedbed at shallower depths (10–15cm) than the conventional ploughing (20-25cm) with a combination of tines, discs and harrows (Cunningham et al., 2004). Leaving overwinter stubbles on dry crop has also been tested for seed-eating farmland birds through various schemes in the UK and has proved to be efficient for farmland bird population increase (Sutherland, 2015).

The large sums of money that are spent on such schemes annually (3.7 billion € in 2003 at the scale of the whole EU in Kleijn et al., 2006) necessitate a clear understanding and a quantification of the response of wildlife to the implementation of particular measures, to assess AES efficiency through cost–benefit analyses and to improve scheme performance if necessary. This question is debated (Kleijn and Sutherland, 2003; Vickery et al., 2004; Kleijn et al., 2006). Governments regularly need to review AES in the light of new research results following an adaptive management or evidence-based approach, in order to increase the cost-efficiency of their investments in AES.

II. Ducks and rice in the French Camargue landscape: the structure and aims of this thesis

Based on the potential links between agro-ecosystems and wildlife described above, considering that the duck-rice system is appropriate for investigating such relationships and in the general framework of optimal foraging and habitat use by these birds in riceland landscapes, the aim of this thesis was to investigate whether **'win–win' agricultural scenarios for rice producers and waterfowl conservation could exist and be further promoted within intensive rice production areas, especially in France.**

II.1 Rice farming and duck conservation

The literature on wild ducks in rice fields is disproportionately represented by studies in the United States, focusing on winter riceland management as a profitable waterfowl habitat during the post-harvest period (Eadie et al., 2008). Studies in Asia rather addressed the agronomic benefits of breeding farm ducks in Integrated Rice–Duck Farming systems (Furuno, 2001). The possibility of specific waterfowl–friendly management procedures providing benefits to farmers for their production and the society through the provision of several ecosystem services has received even less attention (first studies in the U.S. in Anders et al., 2008). Besides the purely agronomic aspects (what the ducks can bring to farmers) and the purely ecological considerations (how field management can promote duck conservation), the present work aimed at following a comprehensive approach to identify the post-harvest practices providing the most ecosystem services. To reach this, we first carried out a literature review trying to summarize the state of the art in waterfowl and rice production relationships worldwide, considering both American and Asiatic studies **(Chapter 1, Article 1)**.

Our hypothesis was:

- There are management procedures that promote mutually beneficial wild duck–rice farming interactions, and minimize the undesired ones.

The main issues addressed were:

-What are the principal constraints and levers of action associated with the management of rice-production areas in a waterfowl–friendly way?

- Are there management procedures that simultaneously promote rice farming and duck conservation?

II.2 Rice farming landscapes and post-harvest practices beneficial to ducks

Two studies indirectly linked to this thesis allowed us demonstrating the combined importance of local habitat management and broader environmental changes at the flyway scale for population size in a given winter quarter (e.g. migration and habitat use strategies of Common Teal *Anas crecca* and Mallard *A. platyrhynchos,* Appendix I.2 and Appendix I.3). In the present work, we considered post-harvest ricefield habitats not only in the Camargue (France), but also in other rice production areas belonging to the East Atlantic Flyway.

The specific objective of **Chapter II** was to characterize the post-harvest managements practiced in the main rice production regions of Europe, and identify those favouring seed resource availability and duck presence.

Straw management impact on seed availability and duck habitat use on rice fields has already been discussed in the US (Eadie et al., 2008; Elphick et al., 2010). The amount of residual grain available to migratory waterfowl at their winter quarters is reduced by the use of faster-growing rice varieties (Stafford et al., 2010), stripper-header harvesters (Stafford et al., 2006; Fleskes et al., 2012) and ploughing (e.g. in the US, Miller et al., 1989 in Stafford et al., 2010). The extent to which straw management (burning, chopping, disking) can influence the use of fields by ducks is unclear (Elphick et al., 2010). However, winter flooding has been proven in the US and in Japan to attract ducks (e.g. Day and Colwell, 1998; Shimada et al., 2000; Elphick and Oring, 2003; Havens et al., 2009; Tajiri and Ohkawara, 2013).

Building on such knowledge, an agri-environment scheme specifically developed for rice cultivation has been implemented recently in Spanish Ramsar sites for waterbirds through the promotion of winter flooding. The AES ‘‘ricefield winter-flooding’’ consists of maintaining the ricefield surface under flooding for at least 3.5 months in Albufera de Valencia (Law: RD 4/2001 and RD 708/2002) and at least 4 months in the Ebro Delta (Council Regulation (EC) No 1257/1999). The extension of the use of such practice in areas where it is not so far financially supported and the response to this AES implementation by waterbird populations had not so far been assessed. However, Toral and Figuerola (2010) showed that population trends at the flyway scale were connected to an index of ricefield availability and use during the autumn in Spain, suggesting that a ricefield winter flooding AES could be very effective to provide suitable waterfowl habitat.

Based on these results, our hypotheses were:

- The regional numbers of dabbling ducks in major rice production regions of the Western Europe are positively correlated with the area of winter flooded ricefields (Article 2).

- The AES ‘‘ricefield winter-flooding’’ implemented in Spanish sites over the last fifteen years is an efficient waterfowl-friendly management that does translate into greater duck numbers during winter (Article 2).

- Availability of seed resources in rice fields is negatively affected by ploughing (Article 3).

- Winter flooding is the major driver of use of rice fields by wintering ducks (Article 3).

The main issues addressed were:

- To which extent is the winter flooding of rice fields practiced in Western Europe? (Article 2)

- Which of the habitat features (area of dry rice, flooded rice, natural and semi-natural wetlands, or their combinations) best explain the regional number of dabbling ducks? (Article 2)

- Has the introduction of an AES ‘‘ricefield winter-flooding’’ in Spanish sites translated into greater local duck numbers? (Article 2)

- Do the post-harvest practices influence the availability of seed resources in rice fields? (Article 3)

- How does the availability of these resources vary across the winter? (Article 3)

- What are the factors influencing the local use of rice fields by wintering ducks (Article 3)?
- What is the initial carrying capacity of rice fields for ducks at the beginning of the winter? (Article 3)

In **Article 2,** we compared the agricultural landscapes of five major rice production regions of Western Europe, all belonging to the same duck flyway (East Atlantic Flyway, see flyway delineations in Scott and Rose, 1996) and assessed their relationship with the number of ducks present on a given site. We considered the six most common European dabbling duck species, i.e. Mallard, Common Teal (hereafter Teal), Northern Pintail *A. acuta* (hereafter Pintail), Northern Shoveler *A. clypeata* (hereafter Shoveler), Eurasian Wigeon *Mareca penelope* (hereafter Wigeon) and Gadwall *M. strepera*. **Article 3** rather focused on one single winter quarter (the Camargue, southern France), where we studied duck foraging use and preference of rice fields depending on post-harvest practices (straw burning, chopping, flooding, ploughing etc…). Due to human and predation disturbance, wintering ducks developed nocturnal foraging strategies (Guillemain et al., 2002; Legagneux, 2007; Martin, 2010). We hence considered rice fields as a potential nocturnal foraging habitat for wintering ducks, evaluated seed banks in such fields and their fate across the winter. Only seeds were considered as part of the duck diet, although we do not ignore that other sources of food such as invertebrates could be available for foraging, and that other seed consumers can be depleting the seed bank besides ducks.

The Camargue was a suitable site for such a study since, as opposed to the other European rice production regions, natural and semi-natural wetlands are still quite well conserved thanks to the combination of large private marshes partly managed for hunting (85% of the area) and many protected natural wetlands (Camargue National Reserve: 13,000 ha, Tour du Valat Regional Nature Reserve: 1,500 ha, Marais du Vigueirat Nature Reserve:

1,000 ha, 'Imperial-Malagroy' departmental reserve: 2,700 ha). The whole Camargue represents ca. 145,000 ha between the two arms of the Rhône river and the Mediterranean sea, 60,000 ha of the delta still being made of wetlands including rice fields (Tamisier and Dehorter, 1999 for detailed site description, see **Figure 4**). Rice is the most widespread crop in the delta (15,000 ha, 61.5 % of the crop in 2011, PNRC, 2013a), either in rotation with wheat, alfalfa (on high lands) or in monoculture (on low saline lands), alternative crops being limited by soil salinity (Barbier and Mouret, 1992).

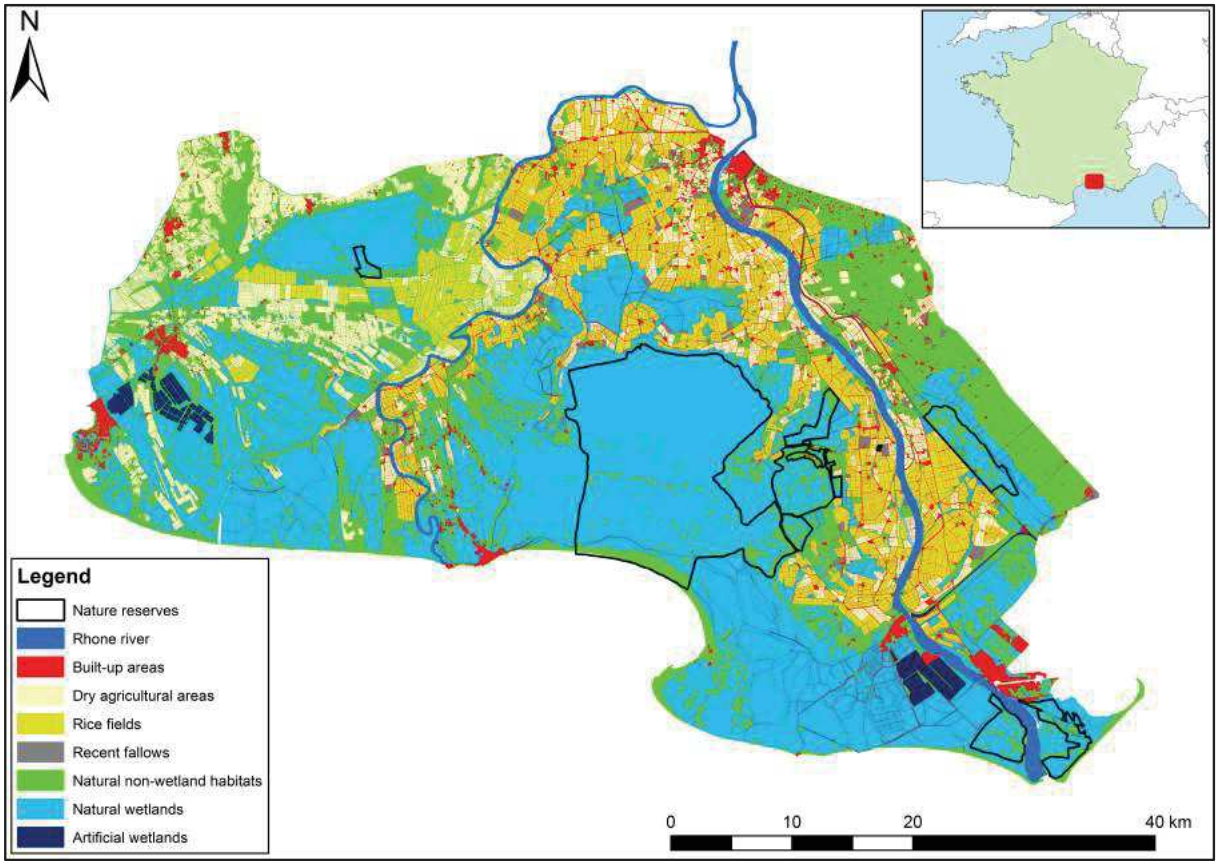

Figure 4. The agricultural-wetland mosaic landscape of Camargue in 2011 (by A. Guelmani from the PNCRC database, PNRC, 2013a).

The Camargue is also the most important winter quarter at the national scale for four of the six studied duck species (i.e., mallard, common teal, wigeon and gadwall, Deceuninck et al., 2014) and one of the most important winter quarters for dabbling ducks at the European flyway scale (Critical Site Network Tool, 2015). Earlier studies have shown the strong degree of interdependence between the various Camargue habitats: ducks mainly gather during the day on natural or semi-natural wetlands with relatively high water levels in protected areas. They only disperse at dusk to reach shallow feeding grounds, principally located in natural marshes and semi-natural hunted marshes, but also including rice fields (Tamisier and Dehorter, 1999, **Figure 4**). The way by which post-harvest practices affect seed abundance and accessibility hence largely determines the possible use of rice fields by wintering ducks for foraging during the night, hence possibly also the overall number of wintering birds in the duck community.

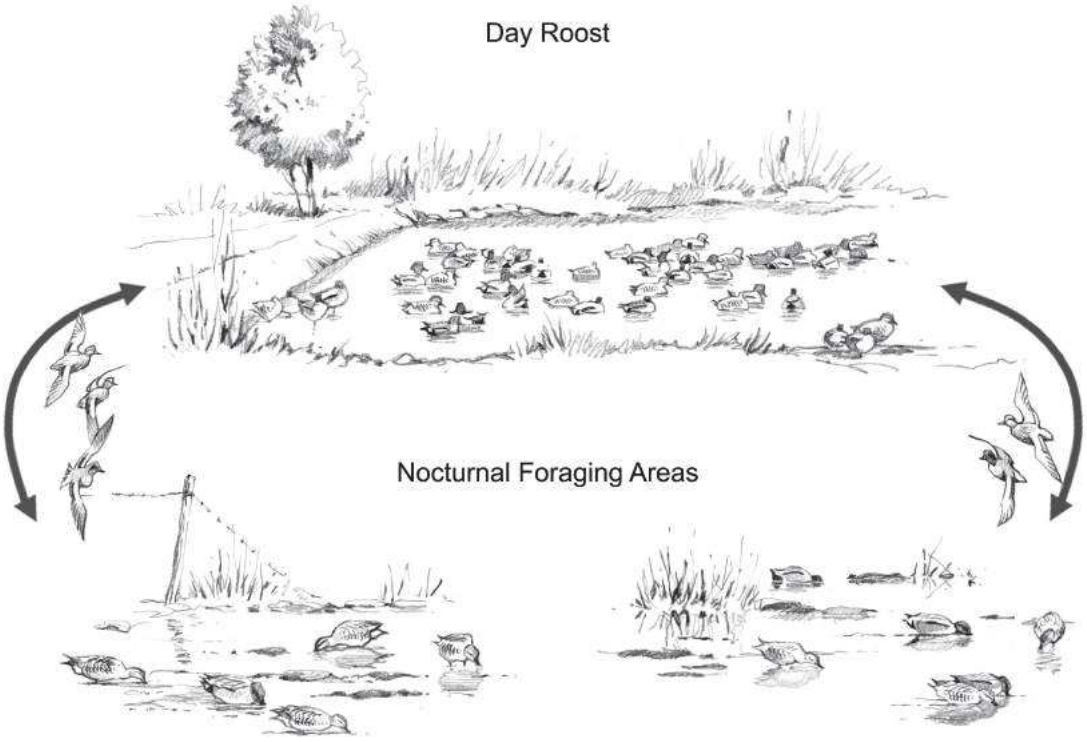

Figure 4. Day roosts and nocturnal foraging grounds of wintering ducks, together forming their functional units (Reproduced from Guillemain and Elmberg, 2014 with kind permission from Bloomsbury publishing).

II.3 Waterfowl-friendly management providing ecosystem services to farmers

Chapter III deals with the ecosystem services that ricefield winter flooding and ducks attracted into flooded fields can bring to farmers. We considered two regulating and supporting ecosystem services, namely weed regulation and straw decomposition improvement. Disposal of rice straw and weed seed management are the main constraints for rice production. In fact, the high silica content of rice straw makes it resistant to decomposition and abrasive, resulting in increased wear and tear of machinery and preventing most of the uses generally made with straw from other crops (Monier et al., 2009). Weeds are also a challenge for rice farmers as they represent a major cause of yield loss (ca. 10 % of total loss on average, Oerke, 2006).

Previous studies showed that winter flooding can improve straw decomposition and reduce weed seed biomass (Manley et al., 2005) or seed viability (Fogliatto et al., 2010; Baek and Chung, 2012), both effects that can be accentuated by foraging wild waterfowl (Bird et al., 2000, van Groenigen et al., 2003). In parallel, other studies reported that rearing farmed ducks on ricelands in Asia prevents the growth of many weeds, and reduces existing weed biomass by trampling and foraging young weed plants and weed seeds (Furuno, 2001).

Based on these results, our hypotheses were:

-Winter flooding is an effective organic management to control rice weeds through the increase of seed deterioration (Article 4)

-Ducks attracted in flooded post-harvest rice fields benefit to farmers through the reduction of weed seed bank by foraging and the reduction of stalks by trampling (Article 5)

The main issues addressed were:

-Does overwinter seed deterioration rate differ between rice and weed species, and depending on whether fields are kept dry or flooded? (Article 4)

-Is seed quality well conserved in flooded ricefield conditions, and hence represents a valuable food stock to wintering ducks throughout the season? (Article 4)

-Can ducks foraging in flooded post-harvest rice fields significantly reduce the number of standing stalks? (Article 5)

-Can ducks foraging in flooded post-harvest rice fields significantly reduce the weed seed bank? (Article 5)

Camargue rice fields are traditionally flooded between seeding and harvest, i.e., from April to September, then kept dry either in stubble, early disked, or ploughed during winter (Mañosa i Rifé, 1997). Currently, approximately 75 % of residual rice straw is burned, the remainder chopped (Monier et al., 2009). While burning straw is currently tolerated, concerns surrounding air pollution through CO_2 Greenhouse gas emissions might soon bring about policy changes that limit or eliminate the practice entirely (Couderc, 2013). In this context, alternative straw management is needed. The small area currently flooded during winter is mostly inundated for waterfowl hunting purposes rather than straw disposal (Mathevet and Mesléard, 2002). Weed control is also a concern for rice growers because climatic conditions and a lower access to pesticides in France (some being non-registered in France while they are in other countries) make the French rice production less competitive than the Spanish or the Italian ones. Furthermore, the Ecophyto national plan decided during the Grenelle Environment Forum (2007) aims to reduce by 50% the use of pesticides in agricultural and non-agricultural areas by 2018. In these conditions, flooding the fields may be an alternative technique to simultaneously limit the weeds and degrade the stalks. In **Article 4**, we experimentally assessed rice and weed seed deterioration in dry and flooding condition across the winter in a greenhouse. An experimental approach was also followed in **Article 5**, although the tests were this time carried out directly in the rice fields, where we assessed the impact of foraging wing-clipped ducks on the weed seed bank and stalks in enclosures.

II.4 Economic valuation of winter flooding in Camargue

Economic valuation of ecosystem services has been advocated by a growing number of environmentalists as a short-term strategy to communicate the value of biodiversity in a language that reflects dominant political and economic views. It can provide complementary insights to purely ecological study results into sustainable ecosystem management and policy (Turner et al., 2000). Several studies have considered wetland or waterfowl ecosystem services, generally documenting a long list of potential benefits and hence calling for a better conservation of these birds or habitats (Green and Elmberg, 2014).

After **Chapters II** and **III**, that assessed the potential of post-harvest practices to provide foraging habitat to wintering ducks and the way by which these birds could in return bring agronomic benefits to farmers, we carried out in the **Discussion** a cost-benefit analysis to evaluate whether winter flooding in France would be economically realistic considering constraints such as water pumping costs, as well as the potential agronomic and environmental advantages for the farmer, and at a greater scale for society (**Article 6, Appendix I.1**).

One of the main conclusions of Manley's (2008) book on "*Conservation in riceland of North America*" was that a precise economic evaluation of winter flooding was still greatly needed. This evaluation should consider the costs of tillage operations, water, reduced input costs, and also potential income from hunting or ecotourism. Such a comprehensive analysis had not so far been carried out, except for the preliminary approach on savings on direct costs by Manley et al. (1999; 2005). This is what we have attempted to complete for the Camargue.

In addition to consider herbicides and fertilizers saving though agronomic benefits, this economic valuation also included other ecosystem services provided by ricefield winter flooding and associated use by wintering ducks, such as cultural services (hunting, birdwatching).

Our hypotheses were:

-Winter flooding in Camargue is economically realistic for the farmer (Article 6)

-Winter flooding in Camargue is economically realistic for the local society (Article 6)

The main issues addressed were:

-What are the market and non-market costs and benefits of different inter crop management sequences (post-harvest scenarios) for the farmer in Camargue? (Article 6)

-What are the market and non-market costs and benefits of different inter crop management sequences (post-harvest scenarios) for the local society? (Article 6)

- Do the benefits of rice field winter flooding outweigh the costs for Camargue farmers? for the general Camargue society? (Article 6)

III. Schematic overview of the PhD thesis

The following framework represents a schematic overview of the thesis organisation, and how the chapters and articles are linked with each other (**Figure 5**).

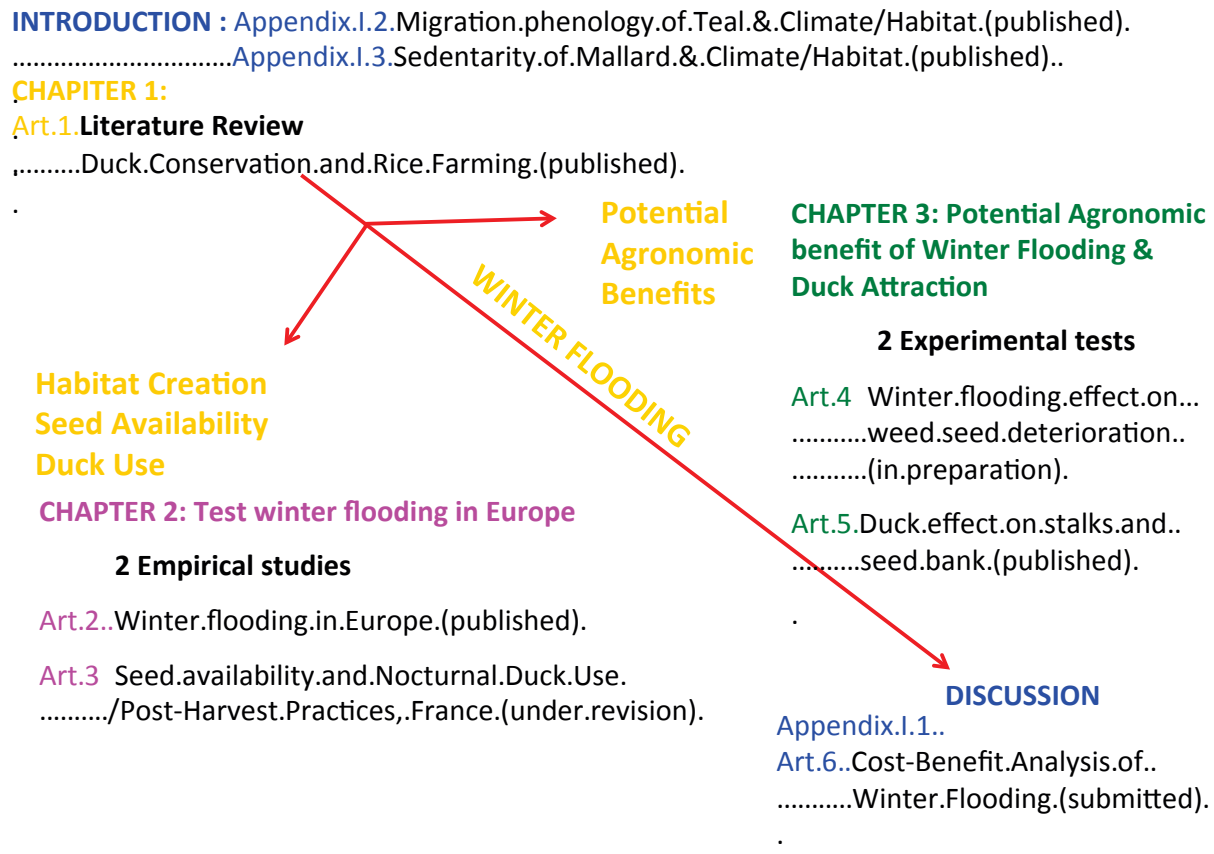

Figure 5. Schematic overview of the three major chapters of the thesis and the articles they contain.

The work carried out in this thesis aims at providing information for evidence-based conservation through a mix of literature review (**Chapter I, Article 1**), empirical (**Chapter II, Article 2 and Article 3**) and experimental studies (**Chapter III, Article 4 and Article 5**). In addition to trying to improve scientific knowledge, the goal was also to provide evidence for practitioners and decision makers and assess the effectiveness of management interventions or support conservation policy. It is for this reason that a few pages expose the general context and methodology then provide the key messages and supporting evidence from the articles at the beginning of each chapter, following recommendation from the Centre for Evidence-Based Conservation website (www.conservationevidence.com).

CHAPTER I. STATE-OF-THE-ART ON RICE FARMING AND DUCK CONSERVATION

Rice-Duck Farming in Indonesia, Andy Wyss

I.1 Background information

Literature reviews are an important source of evidence for practitioners and decision makers, to assess the effectiveness of management interventions or support conservation policy (e.g. Pullin et al., 2004; Pullin and Stewart, 2006; Roberts et al., 2006). The Centre for Evidence-Based Conservation (www.conservationevidence.com) and the Collaboration for Environmental Evidence (www.environmentalevidence.org), a consortium of conservation scientists based in the UK, summarize and synthesize the most relevant knowledge from scientific conservation journals worldwide, paying particular attention to such review articles (Sutherland et al., 2015).

These two consortiums call for ecologists to rely on **"systematic reviews"**, inducing a rigorous methodology, instead of the traditional **''narrative review''** often providing only a qualitative assessment based on the experience and subjective judgment of the author(s) (Gates, 2002; Roberts et al., 2006). Systematic reviews are largely used in medical science, and follow a standardized evidence-based framework (Cochrane method, CRD, 2001). Such methodology has not so far been widely implemented in applied ecological studies (see first attempt in Stewart et al., 2005).

The review article **(Article 1)** presented in this chapter aimed at providing a state-of-the-art summary of the relationships between rice farming and ducks (both farmed and wild), in a broader perspective than the sole topic of the thesis, which focuses on one geographic area (the Camargue) and one period, the winter. As such, this review provides a general understanding of the worldwide context in which the questions of this thesis are framed. We first compiled the known positive and negative effects of rice farming for duck populations and vice versa, then identified the management options by which mutually positive interactions could be promoted and negative ones be relieved. Particular attention was paid to the identification of the economic, social and cultural constraints and the levers of actions. Finally, we pointed out gaps in knowledge and future research needs.

Although this exercise was not a *systematic review* in itself, our work has attempted to follow this approach by: 1) carrying out a detailed systematic literature search combining many sources of information (review articles, scientific articles, grey literature from non-governmental organisations, governmental departments and key experts), 2) presenting quantified data as graphs and tables, including very large summary tables, and 3) reporting the key conservation evidences, identifying evidence gaps and providing management recommendations.

The resources and information used for this review were extracted from:

- Two main reviews themselves prepared by Elphick et al. (2010), "*Ecology and Conservation of Birds in Rice fields: A Global Review*" and Manley (2008), "*Conservation in Ricelands of North America*".

- Scientific literature indexed in the standard Isi Web of Science electronic database (*140 references*).

- Grey literature from non-governmental and governmental organisation websites, including for instance: the FAO-STAT database, the IUCN Red List of Threatened Species webpage, the Critical Site Network Tool for bird distribution, the Birdlife Important Bird and Biodiversity Areas website (*7 references*).

- Grey literature from Master and PhD theses, conference proceedings, technical agronomic or management program reports, such as for example the Proceedings of the first international conference on organic rice farming, the 5th North American Duck Symposium or the 27th International Ornithological Conference; the special issue on *Riz et rizicultures: innovation paysannes et dynamiques scientifiques* by Ahamadi et al. (2013) in Cahiers Agriculture, the BirdReturns project by The Nature Conservancy or the project CORINAT (Coltivazione Riso Naturale in Italy) (*42 references*).

- Grey literature from ornithologist group specialists (Duck Specialist Group; NEOORN Bulletin Board for Ornithologists working with Neotropical Birds, etc…) as well as external experts from institutions such as BirdLife International, Wetlands International, Wildfowl and Wetlands Trust, Durrell Wildlife Conservation Trust, Doñana Biological Station-CSIC, USGS or Mississippi State University, among others.

The main body of our review was a narrative synthesis, however we also compiled quantitative information on graphs and tables whenever possible (e.g. repartition of rice cover in the world put in parallel with the number of Anatidae species that use rice fields and are categorized as pest, threatened or vulnerable species). We also tabulated the duck species that have been classified as rice pests in the literature, the ones which have been recorded breeding in ricelands and finally the agronomic benefits of winter flooding and foraging by wild or farm ducks.

I.2 Key messages and supporting evidence

As suggested by Roberts et al. (2006) for what systematic reviews should eventually come up with, **Article 1** provides a list of key findings. We only highlight here those concerning the management option seemingly benefiting to ducks and farmers the most, which has then been tested in Camargue during the rest of this PhD work, i.e. rice field winter flooding.

Converging evidence points that winter flooding:

1. **improves food resource accessibility to waterfowl in rice fields**. Post-harvest rice fields are readily translated into wintering duck habitat by flooding (review in Eadie et al., 2008). Such management increases the instantaneous number of foraging ducks as well as overall field frequentation (e.g. Day and Colwell, 1998; Shimada et al., 2000; Elphick and Oring, 2003; Havens et al., 2009; Tajiri and Ohkawara, 2013), and can have carry-over consequences on duck population dynamics by influencing their distribution, body condition and survival rates (Fleskes et al., 2005, 2007, 2009).

2. **provides agronomic benefits to farmers** through the increase of nutrient recycling (Manley et al., 1999; Eagle et al., 2000), straw decomposition rate (Manley et al., 2005) and the reduction of weed seed viability (Street and Bollich, 2003; Manley et al., 2005; Fogliatto et al., 2010; Baek and Chung, 2012) (review in Anders et al., 2008 and Table 2 in **Article 1**).

3. furthermore, researchers observed that **waterfowl attracted by flooding can further enhance the benefits of the sole presence of water**. Through trampling and foraging, the birds can further increase straw decomposition, as well as decrease weed biomass in spring (e.g. Smith and Sullivan, 1980; Bird et al., 2000; Van Groenigen et al., 2003; Van Diepen et al., 2004 and Table 2 in **Article 1**).

The literature review also highlighted some important gaps in knowledge regarding the importance of harvested rice fields for waterfowl and the drivers of their use by these birds:

4. Elphick et al. (2010b) reported that the extent to which straw management can influence the use of fields by ducks was unclear.

5. Existing nocturnal surveys (Rave and Cordes, 1993; Cox and Afton, 1997; Tamisier and Dehorter, 1999; Pirot, 1981; Mesléard et al., 1995) revealed that duck nocturnal use of harvested fields is important and deserves a better assessment. Most of the existing waterfowl surveys in ricelands were so far performed during daylight hours (Twedt and Nelms, 1999; Tourenq et al., 2001; Elphick and Oring, 2003; Toral et al., 2011).

6. Consideration on availability of all food sources during winter (Manley et al., 2004; Stafford et al., 2006; Greer et al., 2009; Stafford et al., 2010), the amount of energy and nutrition provided by these resources (Kaminski et al., 2003), and how such calorific value might change across the winter (Nelms and Twedt, 1996) all needed to be more accurately estimated for Duck Use-Days and general carrying capacity of such wintering grounds to be better evaluated.

7. Elphick et al. (2010b) and Green and Elmberg (2014) highlighted that the actual food intake and behaviour of the foraging ducks facing various rice post-harvest practices deserved more attention.

8. King et al. (2010) reported that riceland habitat studies are necessary to implement landscape-scale conservation plans involving both wetlands and flooded agricultural land. Better understanding the drivers behind the movements of waterfowl between natural and artificial wetlands, as well as between their day roosts and nocturnal foraging grounds—i.e., provide a better assessment of the effect of riceland landscape features and heterogeneity (Chan et al., 2007; Elphick, 2008; King et al., 2010; Amano, 2014)- is therefore badly needed.

9. Stafford et al. (2010) called researchers for employing modern tools, such as remote sensing, to investigate trends in rice agriculture worldwide. Other modern modeling tools such as energetic models or multi-agent behaviour-based models (Amano et al., 2006; Petrie et al., 2014; Miller et al., 2014) would help predict the movements and use of the fields by wintering ducks and provide information to guide future conservation planning.

10. Eadie et al. (2008) and Anders et al. (2008) reported that a precise economic evaluation of winter flooding considering the costs of tillage operations, water, reduced input costs, but also potential income from hunting or ecotourism is required.

I.3 Links with the next chapters of the thesis

We used the main results of **Article 1** to guide the empirical and experimental studies set-up in the field and in the lab during this thesis, trying to cover some of the gaps in knowledge listed above and warranted additional research:

11. Nocturnal duck surveys were carried out in Camargue rice fields subjected to different post-harvest practices (**Article 3,** covering points 4 and 5 above).

12. Seed availability after harvest and depletion across the winter were studied in Camargue, which helped to accurately estimate the Duck Use-Days (**Article 3**, covering point 6 above).

13. Energetic content and weed seed degradation across the winter were assessed through an experimental test (**Article 4,** covering point 6 above).

14. Point 7 has not been addressed directly in this PhD thesis but is considered in another PhD work and will result in a joint modeling exercise (refer to **SWAMP project in the Discussion**).

15. Remote sensing has been used to evaluate the composition of European ricelands (**Article 2)** and a first run of the SWAMP multi-agent behaviour-based model (Miller et al., 2014) is currently planned (**SWAMP project in the Discussion**) (covering points 8 and 9 above).

16. A full accounting of the market and non-markets costs and benefits of winter flooding in Camargue has been performed to assess whether such management would be economically acceptable by farmers and by society as a whole (**Article 6** directly covering point 10 above).

Article 1:

Rice and Duck, a good combination? Identifying the incentives and triggers for joint rice farming and wild duck conservation

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Review

Rice and duck, a good combination? Identifying the incentives and triggers for joint rice farming and wild duck conservation

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ABSTRACT

Rice is cultivated in 114 countries worldwide, with nearly half of the world's waterfowl species being directly or indirectly relying on this production during at least one stage of their life cycle. The literature on wild ducks in rice fields is disproportionately represented by studies in North America (although less than 1% of the world's rice fields), while studies in Asia (90% of the worldwide rice production) are mainly focused on the agronomic benefits of breeding farm ducks in Integrated Rice–Duck Farming Systems. In the present literature review we compile knowledge on the interactions between rice farming and ducks, considering positive and negative interactions between the two entities, strategies to alleviate the problems as well as triggers and management options to promote the beneficial relationships. In particular, we focus on (1) the way rice-production areas could be managed in a waterfowl-friendly way, and (2) the agronomic consequences that rice farmers could in return receive from attracting wild ducks or rearing farm ducks in rice fields. For the farmers, the main constraints seem to be associated with duck damages to rice as well as flooding costs. For the ducks, the major issues are habitat loss, homogenization, disturbance and potential disease transmission. However, the present literature review suggests that duck–rice farming is a mutually beneficial association and demonstrates that relatively simple management such as winter flooding can be taken to improve the usability of these habitats to waterfowl, the farmers in turn benefitting from waterfowl ecosystem services.

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1. Introduction

A close relationship exists between bird populations and agricultural landscapes (e.g. Donald et al., 2001; Whelan et al., 2008). In Europe, as much as 30% of observed variation in bird population trends can be explained by fluctuations in cereal production (Donald et al., 2001). While typical farmland birds (e.g. skylark, *Alauda arvensis*) respond readily to changes in their agricultural environment (Chamberlain and Crick, 1999), other species whose associations with farmlands are less obvious can also be impacted. For example, waterfowl (the ducks, geese and swans) are often affected by the transformation of agricultural lands and practices, a common pattern being declines in numbers following the conversion of wet pastures to intensive cereal production (e.g. Duncan et al., 1999). However, the bounty of food made available on such cereal farms is heavily used by some species, especially geese whose populations can increase exponentially (notably *Anser* spp. and *Branta* spp., MacMillan et al., 2004; lesser snow goose *Chen caerulescens*, Gauthier et al., 2005) and some duck species (e.g. cereals in Baldassarre and Bolen, 1984). When considering wet cereal farms, though the conversion of natural wetlands to agricultural lands is inherently damaging to wetland ecosystems, there are often ways to reconcile the differences between the crop's ideal growing conditions and the needs of resident and migratory waterfowl. The focus of this paper is to identify the issues associated with the interaction between the rice industry and wild waterfowl (mainly ducks, both considered as wild and farm birds), and to explore opportunities for ecologically sympathetic ricefield management practices and the incorporation of farm ducks into rice production systems.

Approximately 162 million hectares (1% of the Earth's ice free land surface), or 11% of the world's arable land, is covered by rice fields (FAO-STAT, 2013; Lawler, 2001). Rice is the second most widely grown cereal after wheat, and is cultivated in 114 countries between 50°N and 40°S and up to 2300 m above sea level (Van Nguyen and Ferrero, 2006; Fig. A.1). Rice represents the primary food source for over three billion people, with Asia supplying 90% of global production (Van Nguyen and Ferrero, 2006). Demand for this cereal is expected to continue to grow in coming decades, and production in south Asia alone is predicted to double by 2020 (IRRI, 2000 in Van Nguyen and Ferrero, 2006).

With more than 100,000 distinguishable cultivars, more varieties of rice are grown than of any other crop (Dufumier, 2012). This diversity of cultivars allows rice to be grown in a variety of agro-ecosystems, which can be separated into ten groups based on topography and hydrology, ranging from mangrove swamp rice in tidal zones to hill inland cultivations (see list of such agro-ecosystems in Muzaffar et al., 2010; Wymenga and Zwarts, 2010). Methods of production are also highly variable, and the regime selected is typically determined by freshwater availability and capacity for mechanization. Systems range from traditional low-input to chemically intense, from short (four-month) to long (six-month) growing seasons, from multiple-crop rice-paddy cultivation to slash-and-burn cultivation, and from dry- to deep-water farms (Ibáñez et al., 2010). Chemically intense rice cultivation practices are the norm in North America, Europe, and in parts of Asia, though Asia and also Africa have the majority of the globe's low-input systems. In temperate regions, climatic limitations allow for only a single harvest per year, and fields are typically left fallow during winter months (Ibáñez et al., 2010). In terms of rates of production, the highest volumes of rice come from tropical regions where the climate permits two or even three harvests per year. High rates of production can also be observed on farms that combine rice and animal production, the most common being fish (Halwart and Gupta, 2004), crayfish (Huner, 1994), and ducks (Furuno, 2001), especially in Asia.

Besides farmed ducks, many wild birds also use habitats associated with rice production, including around one third of the bird species found in Japan, Korea, and the Indian subcontinent, and over 20% of the species found in California (Fujioka et al., 2010; Sundar and Subramanya, 2010; Eadie et al., 2008, respectively). Dependency on these habitats varies widely, with some species exhibiting a heavy reliance throughout their life cycle and others using them only temporarily during migration, breeding, or as wintering habitat (Elphick et al., 2010a). Nearly half of the 155 waterfowl species worldwide are directly or indirectly relying on rice production areas (Fig. A.2). This species richness is highest in eastern and central Asia and the continental United States, where important rice-growing regions are located. Although their may be a bias caused by geographic differences in the number of studies, waterfowl species with conservation issues related to rice production seem to be concentrated in eastern Asia, and most waterfowl species in Oceania and Sub-Saharan Africa countries are considered pests by the rice industry (Fig. A.2). Perceptions and acceptance of waterfowl in cultivated areas hence varies by region, depending largely on social and environmental contexts.

Though the globe has lost significant percentages of its natural wetlands over the last century (Finlayson and Davidson, 1999),

artificial wetlands created by agricultural and other industrial activities are sometimes able to mitigate the loss of natural habitat (Czech and Parsons, 2002). Rice fields represent 15% of the world's wetland area (Lawler, 2001), 40% of which are found in China (Wood et al., 2010). Roughly 86% of rice fields are flooded for at least part of the year (Chang and Luh, 1991 in Stafford et al., 2010), and flooded rice fields have been suggested to be valuable surrogates of natural wetlands for some species of waterbirds (e.g. Fasola and Ruiz, 1996; Toral and Figuerola, 2010). The utility of rice fields to waterbirds is debatable, however, and some studies have recorded fewer birds, lower bird species richness, and lower species evenness on rice fields when compared to naturally occurring wetlands (e.g. Tourenq et al., 2001a; Bellio et al., 2009; Guadagnin et al., 2012).

The literature on wild ducks in rice fields is fairly abundant but was first disproportionately represented by studies conducted in the USA and Europe, which together hold just 1% of the world's rice fields. In Asia, where 90% of the world's rice is produced, the relationships between rice farming and waterbirds have only recently started to receive some attention (e.g. in Japan, works of Amano et al. (2004, 2006, 2008, 2011) and in South Korea, Choi and Yoo, 2014). Asian studies so far had more generally addressed the agronomic benefits of breeding farm ducks in Integrated Rice–Duck Farming systems (IRDF, Furuno, 2001). Furthermore, since Asian studies have shown that farming ducks together with rice is an effective technique, there may also be mutually beneficial relationships between rice farming and wild duck populations, although these have received fewer attentions. Rice crop management regimes influence the extent to which wild waterbirds will use rice fields (Ibáñez et al., 2010; Elphick et al., 2010b), but whether both wild birds and rice farmers can benefit from each other has not yet been studied in a general and comprehensive manner. If research can better identify mutually beneficial farming practices, rice farmers may then have incentives to manage their crops in a more duck-friendly way in return for the agronomic services wild birds could provide.

The main objective of this review is to compile knowledge on the variety of issues that affect the interactions between ducks (both farmed and wild) and rice farming. Positive and negative interactions between the two stakeholders are identified, and an assessment is made as to the management options that could promote beneficial interactions and relieve negative ones. Particular attention is paid to the identification of the economic, social and cultural constraints and the levers of actions. Finally, we point out gaps in knowledge and suggest future research that could lead to improved interactions between wild ducks and rice cultivation.

2. Effects of wild and farming ducks on rice farming

2.1. Negative impacts of wild ducks on rice farms

2.1.1. Ducks as pests in rice fields

According to Oerke (2006), some 15% of global rice production is lost to animal pests (invertebrates, rodents and birds). Recently, De Mey et al. (2012) estimated average annual bird damages to be 13.2% of the potential rice production in Senegal, an economic loss of 7.1 million € (equivalent US $8.9 million). Twenty-three species of waterfowl (including 5 of the 8 whistling duck species *Dendrocygna* sp.) have been reported as rice pests at least locally, most of such occurrences being concentrated in Sub-Saharian Africa and Oceania, and to a lesser degree in America and Central Asia (Fig. A.2, Table A.1). It should be noted that the general lack of damages at mid-latitudes in the Northern hemisphere is simply due to ducks in this geographic area mostly using ricefield habitats as wintering grounds, i.e. outside the cropping season. Ducks can damage rice crops by feeding directly on sown grains of rice, on young shoots or young plants in nurseries, or on ripening ears of rice. They can also trample, uproot and foul newly transplanted or growing seedlings (De Grazio, 1978; Katondo, 1996; Lane et al., 1998). One of the more widespread duck-related problems faced by rice farmers is the consumption of emerging rice by white-faced whistling duck, *Dendrocygna viduata* (De Grazio, 1978; Katondo, 1996). The expansion of this duck species into the US coincided with the establishment of rice agriculture in Louisiana, Florida and Texas, highlighting the readiness with which this species exploits rice foraging opportunities (Hohman et al., 1996).

In the US, the abundance of waterfowl in rice-producing areas was historically regarded as detrimental, with yield losses attributed to waterfowl and other wildlife species (e.g. Ellis, 1940 in Eadie et al., 2008). Damages by waterfowl are however typically fairly localized, and the severity of crop destruction often differs profoundly between adjacent farms (Tréca, 1992). While damages from waterfowl in most instances entail limited losses in net income to farmers, they can be so acute and severe as to cause episodes of famine (e.g. in Sahel regions of Africa, Tréca, 1992). In Senegal and Mali, up to ~10–15% of production losses can be attributed to waterfowl, though this figure is generally of lower magnitude (Tréca, 1992). In Tanzania, five waterfowl species contribute to damage from 10% of nursery plants to 30% of newly planted plots (Katondo, 1996).

It should be kept in mind that ducks are not the only birds viewed as pests by the rice industry. For instance, damages by American coot (*Fulica americana*) and flocks of blackbirds (mostly *Agelaius phoeniceus* and *Euphagus cyanocephalus*) up to US $8 million have been recorded in Texas and in Louisiana in the 80s (review in Eadie et al., 2008). Ernoul et al. (2013) estimated the economic cost of greater flamingo (*Phoenicopterus roseus*) damage from 2007 to 2009 in France to be 228€ ha^{-1} (equivalent to US $269 ha^{-1}) in forayed fields, and a total loss of 400,000€ (equivalent to US $472,520) in 2008. No similar recent estimation is available for the cost of duck forays in any country.

It should be noted that the losses to pest ducks by rice farmers in Africa and Asia is sometimes somewhat compensated by the harvest and use of such birds and other aquatic biodiversity as sources of food (Guijt et al., 1995; Ferreyra et al., 2009).

2.1.2. Ducks as vectors of weeds

Ducks not only affect rice farming by reducing yield through foraging and trampling, but can also cause damage through the introduction of weeds. In Europe and North America, *Scirpus* spp., barnyard grass (also called millet, *Echinochloa* spp.) and red rice (*Oryza punctata/perennis*) are the main rice weeds. Owing to the prominent role these birds play in seed dispersal (a process termed "zoochory" see e.g. Figuerola and Green, 2002), concerns have been raised in the US that the large numbers of waterfowl attracted to flooded rice fields could lead to increased weed dispersal. Indeed, the bulk of the diet in four widespread dabbling ducks (Eurasian wigeon (*Anas penelope*), northern pintail (*A. acuta*), mallard (*A. platyrhynchos*) and common teal (*A. crecca*)) in the Western Palearctic is composed of rice (*Oryza sativa*) and *Scirpus* spp. (Dessborn et al., 2011). In the diet of mallard and teal in the Camargue, Southern France, *Oryza sativa*,*Echinochloa* sp. and *Scirpus maritimus* seeds were the most common food items (Brochet et al., 2012). However, Powers et al. (1978) examined the viability of seeds of 17 species of plants collected from the guts of captive mallards, mottled ducks (*A. fulvigula*) and northern pintails, and found that only 2.5% of those seeds germinated under laboratory conditions, with no evidence of seeds of red rice remaining intact and no germination of barnyard grass seed. De Vlaming and Proctor (1968) also demonstrated that of the seeds excreted by waterfowl, only minute percentages are in a viable

condition. Conversely, Brochet et al. (2010) found that an average of 32% of the seeds ingested by teal in the Camargue remained viable post-evacuation. In any case, the abundance of wintering birds and the frequency of their movements led Brochet et al. (2009a) to conclude that migratory ducks are important vectors for rice weeds, including many exotic species (e.g. *Heteranthera reniformis*, *Najas gracillima*). It is clear that weeds are a serious problem to rice farmers. It remains to be demonstrated, however, that this problem is due to the weed seeds transported specifically by ducks to a significant extent.

2.2. Positive impacts of wild and farming ducks on rice farms

In rice production, weeds, crop pests and pathogenic agents can create losses of economic importance to farmers. Oerke (2006) estimated these factors contribute to 37% of losses, with 10% and 15% of this value attributed to weeds and animal pests, respectively. That weeds are the most important biological constraint to rice production can be attributed to the regularity with which rice fields are flooded, which invites a plethora of competitively aggressive wild plants adapted to temporary wetlands. The potential farming benefits of waterfowl using rice fields – in terms of weed control and other agronomic values – has long been recognized (Table A.2). In general, ducks have been incorporated into rice-crop management in two distinct ways. The first is to farm rice and ducks in tandem, with birds being kept at high densities in rice fields during the post-harvest or cropping seasons. This is a traditional practice in Asia and is still widely employed there by rice farmers (Furuno, 2001). The second is practiced in the US, specifically in California and along the Mississippi Alluvial Valley (MAV). Here, extensive areas of post-harvest rice fields are managed in a way that provides habitat to wintering wild waterfowl (Anders et al., 2008). Both systems have proved to be agronomically beneficial (Table A.2).

2.2.1. Rice–duck farming, an agroecological system in Asia

Free-grazing ducks in rice fields during the post-harvest and growing periods dates back to ancient times in China. This traditional method involved allowing as many as 3000 ducks to feed in post-harvest rice fields (Tai and Tai, 2001). Various systems are practiced across Asia today, most of which entail releasing 200–300 ducklings (approximately two weeks old) per hectare into growing rice fields and allowing them to forage until the flowering phase begins (Furuno, 2001). In 1989, Japanese farmer and agronomist Dr. Furuno formalized a now-popular method, "Integrated Rice–Duck Farming" (IRDF, Furuno, 2001), in which flightless domestic "Aigamo" ducks (hybridized mallards and Pacific black ducks *Anas superciliosa*) are kept in rice fields during the growing season (e.g. Furuno, 2001). This method has been adopted by tens of thousands of farmers across Asia and the Middle East (Tai and Tai, 2001).

Farming rice and ducks together has long been appreciated for the reduced need of chemical inputs and the associated economic, environmental, and ecological benefits (recent reviews: Long et al., 2013; Suh, 2014a). By foraging, paddling and ploughing, the presence of farm ducks in rice fields can effectively control weeds, arthropods and gastropods (e.g. golden apple snail, *Pomacea canaliculata*), as well as plant diseases such as rice blast. They also improve the physical structure of the soil, enhancing root growth, soil aeration and soil oxidation–reduction status, the latter reducing methane emissions and preventing accumulation of harmful gases such as NO_2 in the rhizosphere (see Table A.2 and references therein). In addition, duck excreta enrich the soil's nutrients, promoting Nitrogen (N hereafter) fertilizer use efficiency in the ricefield. All of these factors help promote the growth of rice plants, and ultimately contribute to the greater yields frequently observed on IRDF farms.

2.2.2. Winter flooding and the benefits of attracting wild waterfowl

Besides the use of farm ducks in IRDF, flooding rice fields in winter is also a practice employed by rice farmers around the world and promoted for wild waterbird hunting purposes, straw elimination, or environmental conservation (e.g. in North America: Eadie et al., 2008; in Japan: Kurechi, 2007; Tajiri and Ohkawara, 2013). The agronomic benefits of winter flooding include: (1) acceleration of the decomposition of residual straw, (2) decreased weed seed viability, inhibition of germination, and delayed winter weed growth, (3) retention of sediment and nutrients and (4) improvement of water quality (see Table A.2 and references therein). Beyond the direct agronomic benefits of flooding fields in winter, the practice also creates habitat for wintering waterfowl, which in turn works to improve the condition of the land like in the Asian IRDF system. The trampling and shredding by waterfowl foraging after harvest may help to reduce lignin and nitrogen concentrations in the surface residue, increasing rice straw decomposition, soil nitrogen availability, and straw incorporation into the soil. With high duck densities, disappearance of residual surface straw can increase by up to 76% (Bird et al., 2000; Van Groenigen et al., 2003). Wild ducks also reduce the biomass of weed seeds through foraging, providing a reciprocal benefit to farmers (references in Table A.2). In fact, most granivorous duck species worldwide could potentially participate to seed bank depletion when rice fields are made available to them through flooding (read however, Brogi et al., 2015).

2.2.3. Cost/benefit analysis of straw decomposition increase and nutrient external input reduction by winter flooding and ducks

The effects of winter flooding on N dynamics in temperate rice systems have not been studied extensively. It is known however that winter flooding can reduce the need for external N input by increasing the level of soil organic N, a phenomenon attributed to microbial communities adaptating to an extended anaerobic time period (Eagle et al., 2001 in Anders et al., 2008). Though the long-term effects on yield are unknown (only one example of 8-year research program, Bird et al., 2002), by winter flooding their fields North American farmers enjoy reduced tillage requirements and reduced costs of preparation for spring planting, saving the equivalent of US \$22–63 ha^{-1} (Stafford et al., 2010). Manley et al. (2005) suggested that by holding winter water until the beginning of March and leaving stubble in the field, rice growers could eliminate two passes of a disk in autumn, saving US \$34.22 ha^{-1}. Farmers can otherwise spend up to US \$125 ha^{-1} in chopping, ploughing or disking residual rice straw (Bird et al., 2000).

Waterfowl foraging could also influence nutrient availability indirectly through increased decomposition of straw and directly by nutrient inputs. China consumes more than one quarter of the world's N fertilizer with low fertilizer N use efficiency (20–40%) (Cheng-fang et al., 2008). Duck excreta from rice–duck farming are rich in N and provide an organic fertilizer that could reduce both financial costs for Asian farmers and detrimental impacts on the environment. With 200–250 ducks ha^{-1} and about 150 g droppings per day $duck^{-1}$, about 10,000–12,000 kg of faeces are recycled in one hectare every year (Subramanian et al., 1996). While this can be extremely beneficial for the reasons listed above, there have been documented instances of over-fertilization and contamination of the waterways resulting from excessive concentration of farming ducks (Roh et al., 2009), the same being observed on wetlands with high wild waterfowl concentration (Post et al., 1998). A recent study in southwestern Europe has demonstrated that geese and dabbling ducks can improve nutrient recycling in rice fields through consumption of rice seed leftovers and

defecation. In that case, the authors calculated a nutrient waterbird recycling (mainly waterfowl and common cranes, *Grus grus*) of more than 24.1 t (1.0 kg ha^{-1}) of N and an additional 5.0 t (0.2 kg ha^{-1}) of P during winter (Navedo et al., 2015).

2.2.4. Cost/benefits analysis of rice weed and invertebrate control by ducks

Weeds present major problems for rice farmers, and are a serious limitation to the development of organic rice farming, for which there is a growing demand (INRA, 2012). The rice industry incurs significant monetary losses through weed control and prevention; lower yields where rice and weeds compete, and reduced quality of the harvested crop following herbicide and pesticide application. In Sri Lanka, ~20–30% of rice yields are lost to competition with weeds (in Baki et al., 2000), the figure being ~28–100% in West Africa in areas where weed growth is uncontrolled (Rodenburg and Johnson, 2009). Across West Africa, the annual yield lost to weeds was evaluated to be at least 2.2 million tonnes, equating to an economic loss of US $1.5 billion (Rodenburg and Johnson, 2009).

Rearing ducks on ricelands in Eastern Asia prevents the growth of many weeds, and reduces existing weed biomass by trampling and foraging young weed plants and weed seeds (Table A.2). In Japan, Furuno (2001) estimated that 240 manual weeding hours per hectare could be saved annually by using farm ducks. In the Philippines, Barroga et al. (2007) considered a significant reduction of need for workers for weeding, fertilizer application and chemical spraying. Along with farm ducks, wild ducks and other waterbirds also consume weed seeds in flooded fields, and may thus reduce the need for herbicides. As early as in the 1920s, MacAtee (1923) estimated that waterfowl feeding on red rice saved Arkansas US $150,000 (in Anders et al., 2008). Later, Smith et al. (1977) and Hobaugh et al. (1989) calculated that the US rice industry could annually save up to US $290 million by promoting winter flooding and exploiting the weed controlling abilities of waterfowl (in Anders et al., 2008). Anders et al. (2008) calculated that if an aerial application of herbicide could be omitted, US $28.71 ha^{-1} could be saved. Producers in the MAV have estimated that winter water management can save up to US $49.42 ha^{-1} on chemical and tillage costs annually (Muzzi, 1994 in Anders et al., 2008).

In addition to plant matter, waterfowl also use invertebrates substantially as food in rice fields (Hohman et al., 1996). Manley et al. (2004) calculated 13.6 kg ha^{-1} of aquatic invertebrates were available in winter-flooded rice fields in the MAV. While invertebrates represent a small fraction of potential forage for most duck species during winter, they constitute a high-energy food and contribute to nutritional protein requirements of wintering waterfowl and of ducklings (Miller, 1987 in Eadie et al., 2008; Miles et al., 2002, respectively), and make up the bulk of the diet of some species such as the northern shoveler (*Anas clypeata*) (e.g. Tietje and Teer, 1996). Some of the invertebrates on which ducks prey are considered rice crop pests, and so their consumption by ducks could also be a service to rice farmers. For instance, northern shoveler will prey on crayfish, which are a destructive force in crops and rice field levees (Phillips, 1923), and fulvous whistling ducks foraging in Louisianan rice fields preyed on oligochaete worms (Hohman et al., 1996). The golden apple snail (*P. canaliculata*) introduced to Asia ravages rice crops, while another South American species (*P. insolarum*) recently began doing the same in Spain (Ebro Delta). Losses to these exotic pests in Asia run into millions of US dollars (Naylor, 1996), and ducks in IRDF systems have proven an effective counter-measure (Table A.2). Wild ducks such as mallards could be efficient predators too (Yusa et al., 2006).

Rice production systems can also play a role in the emergence and resurgence of some epidemic diseases through the promotion of some invertebrate populations, mostly mosquitoes, a consequence of the similarities between wet-rice lands and the semi-aquatic ecosystems where some diseases persist. In the Camargue, Southern France, Ponçon et al. (2007) demonstrated that two species of mosquito, *Anopheles hyrcanus* and *Culex modestus*, known vectors of both malaria and West Nile Virus, have been documented to increase in abundance with rice cultivation expansion. Post-harvest practices such as winter flooding and burying rather than burning-straw favour certain insects like mosquitoes, and may therefore contribute to the persistence and transmission of diseases (Lawler and Dritz, 2006). While it is true that duck-friendly rice field management may simultaneously benefit mosquitoes, ducklings do also forage on these (Miles et al., 2002) so that ducks may in turn reduce the density of mosquito larvae (Batzer and Resh, 1992).

2.2.5. Methane/N_2O gas emission, increased by flooding and decreased by ducks

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHG), and together with carbon dioxide (CO_2) are responsible for about 88% of global warming (Malla, 2008). Agricultural systems that use nitrogen fertilizers for soil amendment contribute greatly to anthropogenic N_2O emissions (80% of the anthropogenic concentration; Zhang et al., 2008). The flooded conditions of rice cultivation result in high CH_4 emissions (28–367 kg ha^{-1} season^{-1} after Malla, 2008). However, CH_4 emissions are lower when water depths are greater (Fu et al., 2006) and N_2O emissions can be decreased if paddy fields are drained mid-season (Ortiz-Monasterio et al., 2010). Flooding of rice fields to host waterfowl may therefore be detrimental in terms of greenhouse gases, but rice–duck farming has actually been shown to help reducing methane emissions from paddy fields, owing to increased oxidation of sediments by bioturbation (Table A.2). The effect of wild waterbirds on greenhouse gas emissions has not been evaluated yet. However, a recent study assessed the potential impacts of post-harvest agricultural practices that reduce GHG emissions on waterbirds (see Sesser et al., 2014).

2.2.6. Yield: are ducks economically beneficial to rice farming?

Several studies reported that IRDF frequently leads to higher crop yields than farms growing rice in the absence of ducks (Up to 20% in Bangladesh, Hossain et al., 2005). Economic gains can also be made through reduced costs associated with weeding labour, pesticides and chemical fertilizers, and when considering the additional income from the selling of ducks, higher total net returns per hectare can be achieved with IRDF systems when compared to those of conventional farming (Up to 50–60% in Bangladesh, Hossain et al., 2005).

Whether or not similar benefits exist when rice fields are managed sympathetically for wild waterfowl has not been confirmed, and an evaluation of crop yields where waterfowl are attracted to rice fields is required. However, some preliminary elements already exist (Bird et al., 2002; Navedo et al., 2015). Although winter flooding did not seem to adversely affect yields in North America (Eagle et al., 2001 in Anders et al., 2008), Anders et al. (2008) dispute the idea that winter flooding benefits soil conditions. Van Groenigen et al. (2003) demonstrated an important decrease in weed biomass through waterfowl activity, but no significant yield differences were observed between rice areas visited by waterfowl and those with waterfowl exclosures. Direct benefits of waterfowl foraging may be observed only in extremely weedy fields or where producers are not dependent on herbicides for weed control (Anders et al., 2008).

Depending on a number of factors, the flooding of rice fields can also be a relatively expensive endeavour. The operational cost of purchasing, moving, and holding water can be significant and

varies greatly between regions (Anders et al., 2008). In the MAV, where much of the water used by rice farmers is impounded rainfall kept with simple water-control structures, the cost of flooding fields is generally low (Manley, 1999 in Anders et al., 2008). Conversely, in Texas water is supplied and pumped by irrigation companies, and here the cost of flooding rice fields is consequently much higher (Hobaugh et al., 1989 in Anders et al., 2008). Water must also be purchased in California, with restrictions in place regarding the amount an entity can purchase. In that area, the total cost of flooding rice fields in winter can be as high as \$53.13 ha^{-1} (Williams et al., 2001 in Anders et al., 2008).

To establish whether the benefits of flooding rice fields for wintering ducks outweigh the costs, precise economic evaluations still need to be done in North America and the other major rice producing areas where winter flooding is applied. In addition to agronomic factors, potential revenue from hunting leases or ecotourism and subsidies to promote environmentally-friendly practices should also be considered when making the calculations (Eadie et al., 2008).

3. Effects of rice farming on wild ducks

3.1. Negative impacts of rice farming on wild ducks

3.1.1. Habitat loss

Over 50% of natural wetlands worldwide have disappeared since 1900, mainly to urbanization and agriculture conversion (Fraser and Keddy, 2005). In 1985, Finlayson and Davidson (1999) estimated a loss of 65% of wetlands in North America and Europe. The Mediterranean region has seen the greatest losses, with estimates putting losses at ~80–90% (Finlayson et al., 1992). Sub-tropical and tropical wetlands have come under increasing pressure since the 1950s, with losses in the 80s estimated at 27% for Asia, 6% for South America, and 2% for Africa (Finlayson and Davidson, 1999). In the Mediterranean, around 23% of the remaining wetlands are artificial, many of these being rice fields (in addition to e.g. salt pans or irrigation reservoirs) (Perennou et al., 2012). In a recent wetland assessment, Davidson (2014) reported that in China between 1978 and 2008, such artificial inland wetlands increased by 122% while natural inland wetlands decreased by 33%.

Rice expansion is often done at the expense of natural habitats, and many large and continuous tracts of wetlands are now reduced and fragmented as a result. For example, in major rice production areas wetlands have decreased by e.g. 89% in Arkansas within the past 200 years (Dahl, 1990 in Eadie et al., 2008), and less than 5% of the natural wetlands present in the mid 1800s in the California valley exist today (Fleskes et al., 2005). Similarly, in the Spanish Ebro Delta 71% of natural wetlands are now used as rice fields (Mañosa i Rifé, 1997).

Global rice production has arisen by nearly 180% and cultivated areas increased by 25% since the mid-1960s (Donald, 2004). The expansion in rice area worldwide was estimated by Balmford et al. (2012) at 40,000 ha $year^{-1}$, almost equivalent to oil palm (50,000 ha $year^{-1}$). However, rice expansion is not occurring at the same pace in all continents, and is currently expanding the fastest in Africa, particularly in the western part of the continent (Wymenga and Zwarts, 2010). Rice is often grown at relatively low latitudes, so that habitat loss to rice is often limited to the wintering grounds of migratory ducks, rather than their migration stopovers or breeding habitats. However, in tropical countries, it is grown over the largest area (18% of tropical cropland) being the most widespread crop in the moist broadleaf forests, in the dry broadleaf forests and in the mangrove biome (Phalan et al., 2013). In places such as Australia and Madagascar, rice expansion negatively affects sedentary duck species (cf. paragraph below).

Many studies have compared the diurnal bird communities of natural wetlands and of rice fields to determine if the latter could be valuable substitutes or complements to natural wetlands in terms of waterbird conservation (e.g. Fasola and Ruiz, 1996; Toral and Figuerola, 2010 versus Tourenq et al., 2001a; Bellio et al., 2009). Rice and other artificial wetlands represent poor habitats for some waterfowl (e.g. marbled teal *Marmaronetta angustirostris*, A. Green pers. comm., see also Rendón et al., 2008; King et al., 2010). In Australia the conversion of natural wetlands into riceland is considered to have contributed to population declines in waterbirds since the 1960s (Taylor and Schultz, 2010). Although ricelands can be used by waterfowl under some conditions, the conversion of natural habitats (wetlands, forests or grasslands) into rice fields does reduce and fragment the original habitat area of some species (Guadagnin and Matchick, 2007 in King et al., 2010), some of them being directly threatened by such reduction (e.g. in Africa, the critically endangered Madagascar pochard *Aythya innotata*, endangered Madagascar teal *Anas bernieri* or endangered Meller's duck *Anas melleri*, G. Young pers. comm.; BirdLife International, 2013 in IUCN, 2014 and in Asia, the globally endangered white-winged duck *Asacornis scutulata* in Sumatra or the Philippinne duck *Anas luzonica*, BirdLife International, 2013 in IUCN, 2014).

3.1.2. Reduced habitat quality and homogenization of the landscape

Advancements in technology and methods since the Green Revolution (1960s) have resulted in the loss of traditional systems of production, which were often more ecologically benign in terms of: (i) rice varieties, (ii) irrigation and planting systems, and (iii) general landscape heterogeneity (Donald, 2004). Broadly speaking, riceland landscapes have become simplified and homogenized. Laser-levelling field cultivation practices allow more efficient water management (Eadie et al., 2008), but may reduce water depth heterogeneity which benefits a greater range of waterbirds (Elphick and Oring, 2003). In Japan, 80% of the old diversion irrigation systems of rice production have been replaced by modern subterranean pumping systems, with possible negative consequences on frogs and waterbirds (Fujioka and Lane, 1997; Lane and Fujioka, 1998 in Donald, 2004, respectively).

The abundance and spatial configuration of ricelands versus natural habitats can be more important for maintaining a high diversity of birds than the surface area covered by rice crop itself (e.g. Chan et al., 2007; Amano et al., 2008). The fragmentation of natural habitats and artificialization and homogenization of rice growing landscapes may reduce habitat connectivity and decrease the permeability of agricultural matrices (King et al., 2010), with negative consequences for waterbirds and sometimes to farmers (see however Katayama et al., 2014). In fact, waterbird damages can increase following removal of habitat features such as hedges or wooded margins (e.g. greater flamingo, Tourenq et al., 2001b; greater white fronted geese, Amano et al., 2004). However, the responses of waterbirds to the condition of rice-dominated landscapes vary between species and no single management prescription will work for all taxa (Elphick, 2008).

Finally, in places where water supply is an issue (e.g. South Spain, California, West Africa), competition for water between natural wetlands and irrigated agricultural fields is concerning. For instance, the construction of dikes and dams for rice agriculture in the Senegal River Valley is threatening the Djoudj National Bird Park, where the hydrology has been altered and agrochemical pollution has become a major concern (Schuyt, 2005).

3.1.3. Pollution through use of agrochemicals

Most rice fields are extensively managed with pesticides and fertilizers. Modern rice cultivation typically uses around 20% of the total agricultural nitrogen fertilizers used in agriculture (Ahmadi

and Bouman, 2013) and no less than 274 active compounds (83 insecticides) have been registered for controlling weeds or animal pests in rice production (Parsons et al., 2010). Pesticide use is a major concern for foraging aquatic birds because of direct mortality by poisoning and indirect effects by ingestion of contaminated food and/or reduction of food resources (Parsons et al., 2010; Ibáñez et al., 2010). Much evidence exist linking pesticide use to trophic cascades through non-target invertebrates, with prey availability for waterbirds being subsequently reduced (e.g. Miles et al., 2002; Mesléard et al., 2005). Herbicides also reduce food availability, weed seeds being important forage for granivorous waterbirds (Tourenq et al., 2003). The recent advent of genetically modified (GM) rice varieties and associated use of herbicides that kill all plants except the GM varieties may also reduce the abundance of weeds and the food available to waterbirds (Taft and Elphick, 2007).

Several studies reported ducks being inadvertently killed or seriously affected after consuming contaminated food, particularly when feeding on seed-eating invertebrates in the presence of certain agrochemicals (e.g. Flickinger and King 1972; Osten et al., 2005 in Parsons et al., 2010). The situation seems to be the most critical in the Indian subcontinent where accumulation levels of certain agrochemicals (e.g. organochlorine insecticides) in both resident and migratory birds is the highest in the world (Sundar and Subramanya, 2010). Since the mid-1990s, China has likely been the world's largest user of agrochemicals (Wood et al., 2010), and agrochemical imports have been increasing exponentially across Southeast Asia (Horgan, 2012).

In addition to being unintended victims, birds are themselves sometimes the target of chemical pest control. Some farmers concerned with waterbirds in their rice fields have treated rice seeds with toxic substances called *avicides* prior to planting, or sprayed the substance directly onto their fields. This is illegal in most places, and occurs primarily in Africa (e.g. 1.8 million passerines killed in Uganda in 2013) and South America (Blanco et al., 2006).

3.1.4. Hunting and human disturbance—rice fields as ecological traps

As mentioned above, the harvest of wild birds that use rice fields is sometimes an important source of protein to farmers (Guijt et al., 1995), and the majority of American and European rice farmers that flood their fields after harvest do so to attract ducks for leisure hunting purposes (Elphick et al., 2010b). In North America, 75% of rice fields in California (Garr, 2002 in Eadie et al., 2008) and more than 95% of those along the Gulf Coast (Elphick et al., 2010b) are flooded to attract birds for hunting. In some areas the annual influx of ducks to rice fields has prompted the creation of businesses serving recreational hunters. The USA waterfowl hunting economy was worth in excess of $27 million at the end of the last century (US 1999) (Grado et al., 2001 in Eadie et al., 2008). Ten years after, it has been reestimated to $86.8 million (US 2009) (Grado et al., 2011). In the Camargue, Southern France, Mathevet and Mesléard (2002) estimated that shooting generates about €4.4 million (equivalent US $5.2 million) in lease income annually, a good proportion of this activity occurring on or in close proximity to rice fields.

Some waterbird species under-exploit suitable winter feeding grounds due to disturbance caused by hunting (Madsen and Fox, 1995). Rice fields may also become ecological traps, as birds enticed by habitat and abundant food resources – often in the form of bait – are subsequently killed by hunters or poisoned by lead (e.g. Mateo et al., 2000; Ferreyra et al., 2009).

3.1.5. Sanitary problems

The Asian continent accounts for 82.6% of worldwide duck meat production (Adzitey and Adzitey, 2011). Ducks in IRDF systems in Asia are sometimes believed to contribute to the persistence and transmission of harmful diseases. Asian IRDF systems maintain vast free range flocks of ducks that forage in both rice fields and wetland areas. Depending on food availability in post-harvest fields, flocks of birds are regularly herded over great distances. In Vietnam this happens between November and March with a peak in December, (Men, 2010) coinciding with the influx of migratory birds to the rice-growing regions (Li and Mundkur, 2007 in Muzaffar et al., 2010). The subsequent mix of domestic and wild birds is believed to contribute to the transmission of pathogenic agents. This was particularly true for the spread of highly pathogenic avian influenza (HPAI) (Gauthier-Clerc et al., 2007). In that case, geospatial analyses demonstrated that during the first epizootic waves of the winter 2004–2005, the persistence of HPAI H5N1 in Thailand was primarily associated with irrigated rice areas in river deltas, plains, and other wetland areas where tens of millions of free ranging farm ducks were located (Gilbert at al., 2007 in Muzaffar et al., 2010). When the disease re-emerged in Vietnam in early 2007, the Animal Production Department of the Ministry of Agriculture and Rural Development concluded that the free-grazing duck system was the major cause of the persistence of HPAI in the Mekong Delta, where the majority of the country's two million households practicing IRDF herding systems are located (Men, 2010). In general, the numbers of dead and infected wild birds with HPAI H5N1 have so far been trivial despite continuing outbreaks in poultry in Asia and Africa (Feare, 2010). The geographical and phenological patterns of spread of this virus do not always correspond with bird migration patterns, and no evidence exists of HPAI viruses persisting long-term in the wild (Gauthier-Clerc et al., 2007). Thus farm ducks are likely an important source of pathogenic agents for wild ducks. However, a recent study modelling the occurrence of influenza A virus in Japan showed that the numbers of wild dabbling duck was a better indicator of avian influenza virus introduction than was the poultry density in the area, and that in the past avian influenza transmission were from wild birds to poultry rather than the opposite (Moriguchi et al., 2013). The debate therefore is still open, and the situation may depend on regional factors.

3.2. Positive effects of rice farming on wild ducks

The importance of artificial wetlands has been recognized by the Ramsar Convention on Wetlands, and the definition of wetlands has been broadened to include reservoirs and rice fields (e.g. Ramsar, 2008 in Rebelo et al., 2010). Man-made wetlands are particularly important for waterfowl during dry seasons or periods of drought when natural wetlands become scarce (for rice fields: Tourenq et al., 2001a). They are particularly important in the Sahel, where at the end of the dry season irrigated rice fields are among the very few wetland habitats still available to waterbirds (Wymenga and Zwarts, 2010). Some fishponds or irrigation reservoirs constitute disturbance-free areas and are extensively used by ducks as daily roosting sites, with foraging taking place at night in nearby rice fields (fishponds: Rendón et al., 2008; irrigation reservoirs: Navedo et al., 2012). Rice paddies are used by waterfowl as nest sites, safe roosts, migratory stopovers and winter foraging sites (Elphick et al., 2010a).

3.2.1. Rice fields as duck breeding habitat

Because most duck species breed at higher latitudes than those where rice can be grown, only a handful of duck species (Table A.3), including fulvous whistling duck and mottled duck in Louisiana and mallard in California (Hohman et al., 1996; Durham and Afton, 2003; McLandress et al., 1996, respectively in Pierluissi, 2010), have been observed nesting in standing rice crop, on levees within fields or in associated irrigation canals. Though resource availability and

the relative effects of agricultural practices during the growing season have not been thoroughly assessed (Stafford et al., 2010), some research on this topic has been done. Krapu and Reinecke (1992) found that flooding rice fields from late winter to early spring provided more invertebrate forage for pre-breeding waterfowl. Hohman et al. (1994) tested the influence of seeding techniques and density of rice plants, and observed that the nest success of fulvous whistling ducks was twice as high in water-seeded fields than those dry-seeded, and that nest densities tended to be greater in more sparsely vegetated rice crops. Mallard brood survival was influenced by the timing of rice field flooding, with higher rates of predation when early-hatched ducklings were not protected by high emergent rice cover (see Taft and Elphick, 2007).

3.2.2. Rice fields as duck roosting habitat

Ricelands can provide safe roosts for resident or migrating ducks. Ducks using non-hunted flooded rice fields as day-roosts during migration include northern pintail (Rave and Cordes, 1993) and mottled duck in Louisiana (Durham and Afton, 2003), but this phenomena is more frequently associated with geese (e.g. in Texas, Czech and Parsons, 2002; in California; Ackerman et al., 2006 in Stafford et al., 2010, in Japan, Fujioka et al., 2010) or on rice fields restored into wetlands (e.g. Kurechi, 2007). Human disturbance linked to either farming or hunting activities otherwise often precludes the use of rice fields as day-roosts.

3.2.3. Rice fields as foraging and refuelling habitat

Rice growing regions are found at low to mid-latitudes, and are therefore most often used by ducks as migration stopovers or wintering grounds. Given the cultivation cycle of most rice fields, migratory ducks typically reach rice areas when harvest is completed. Still, the birds enjoy bountiful harvest leftovers, weed seeds and invertebrates. Studies in the MAV (Rave and Cordes, 1993; Cox and Afton, 1997) and France (Tamisier and Dehorter, 1999) indicate that rice fields are mostly used nocturnally, likely in response to diurnal disturbance and hunting pressure. Differences in levels of human disturbance generate a high variability in the density of ducks using rice fields worldwide, and given that duck foraging activity is highest at night, the use of such areas must be often underestimated. Published diurnal densities of waterfowl in harvested rice fields range from 5 to 10 birds km^{-2} in France (Tourenq et al., 2001a) and the MAV (Twedt and Nelms, 1999), about 30 birds km^{-2} in Japan (Fujioka et al., 2010), and as much as 730 birds km^{-2} in California (Elphick and Oring, 2003). Estimates of nocturnal waterfowl densities in rice fields are few (e.g. none is available for California, Eadie et al., 2008), but given the diel changes in activities and habitat use exhibited by ducks, should be greater than diurnal densities in the same fields (McNeil et al., 1992). Nocturnal counts conducted with light amplifiers in the Camargue, Southern France, yielded mean densities of 5–24 ducks ha^{-1} (Pirot, 1981; Mesléard et al., 1995 and C.A. Pernollet et al., unpublished results).

3.2.4. Summary: do ducks benefit from using rice fields in terms of demography?

Whether the provision of attractive rice fields and the management practices on these fields provide long-term, flyway scale benefits in terms of waterfowl population dynamics is largely unknown. The only practices that have been tested repeatedly is winter flooding associated with specific post-harvest stubble management practices, and these were found to affect local duck numbers (e.g. Day and Colwell, 1998; Shimada et al., 2000; Elphick and Oring, 2003; Havens et al., 2009; Tajiri and Ohkawara, 2013; Pernollet et al., 2015). In the Spanish Ebro Delta the residence time of wintering ducks was recorded to increase after lengthening the winter flooding period (Ferrer, 1986 versus Oltra et al., 2001). In California, ducks wintering in the San Joaquin Valley moved towards the rice-growing region of the Sacramento Valley when rice fields there were flooded (Fleskes et al., 2005). These ducks were also reported to have an improved body condition and increased survival rate (Fleskes et al., 2007, 2009).

The provision of rice habitat may facilitate population growth of already overabundant species, and was recorded as the primary reason for the expansion of the white-faced whistling duck (Hohman et al., 1996) and lesser snow geese in the US (Eadie et al., 2008). In the same way that these species expanded their ranges, threatened species can also benefit from the rice field-associated resources, as was the case for the vulnerable west Indian whistling duck (*Dendrocygna arborea*) in Cuba (Acosta et al., 2010) and the now-least concern baikal teal (*Sibirionetta formosa*) in Japan (Tajiri et al., 2014). Conversely, changes in rice cultivation practices may cause declines in waterfowl species traditionally using such habitats, calling for biodiversity-friendly management of rice fields (see Kasahara and Koyama, 2010; for Japan). Such agri-environmental schemes (e.g. flooding of harvested fields) can rapidly provide habitat to waterfowl populations, and hence boost their populations very quickly (Pernollet et al., 2015; for Europe). More globally, Toral and Figuerola (2010) provided a population-scale look at habitat and duck demographics, concluding that a positive relationship exists between European waterbird population trends and an index of rice field availability and use during the autumn in Spain.

4. How to promote the mutually beneficial services and alleviate the problems?

The above review highlights many ways by which rice farming can benefit ducks and the services that ducks can provide to farmers. A number of hurdles to such mutually beneficial relationships have also been listed. Below we highlight measures that could be taken to alleviate the problems existing between ducks and the rice industry, and ways to promote the positive relationships between the two.

4.1. Reduction of negative interactions

4.1.1. Control of wild duck damage

The most important negative effect wild ducks have on rice farming is crop damage. Three measures should be taken when facing such damages. First, a fine economical quantification of the actual severity of the damages should be performed (Ernoul et al., 2013; MacMillan et al., 2004). Second, the factors influencing crop vulnerability should be identified, and if severe and widespread, an economic assessment of the possible ways to reduce or mitigate the damages should be made (e.g. Tourenq et al., 2001b). Third, when the damages are localized, a financial compensation to them could be considered (e.g. Wagner et al., 1997).

Scaring devices (audio or visual deterrents) are the most common mitigating measures used during the critical stages of rice growth, i.e. around sowing and during early seedling growth (Parsons et al., 2010; Taylor and Schultz, 2010). As an alternative to forbidden avicides and other lethal repellents, shot controls are sometimes performed by state officers or directly by local hunters. In rice fields where certain ducks are viewed as pests (cf. Table A.1), sport hunting is authorized to mitigate crop damage (e.g., in Argentina, Ferreyra et al., 2009).

In the Sahel region, more agronomical and ecological techniques have been proposed to reduce duck damage. These include: (1) a flexible sowing date to avoid peak duck migration periods; (2) selecting rice varieties that mature simultaneously and over a relatively short period; (3) reducing open water to minimize the attractiveness of the area to ducks; (4) improvement of the

irrigation systems to ensure early and rapid field drainage before full rice maturity; (5) provision of undisturbed natural foraging habitats that guarantee enough food for ducks (Tréca, 1992). When socially and economically acceptable to do so, some crop area might be strategically set aside specifically for birds as Alternative Feeding Areas (AFAs) (Vickery et al., 1994). This idea can be pushed further, and in regions where growing seasons are short (e.g. Gulf Coast Region of the southern USA) farmers can obtain a second or "ratoon" rice crop by simply re-flooding harvested fields without re-seeding. Most of the time this production is not harvested and is left for waterfowl to forage. Stafford et al. (2010) suggest this should be encouraged by conservation organizations and governmental incentives where climate is favourable.

4.1.2. Reduced conversion of wetlands into rice fields

The most important negative effect of rice farming on wild ducks is the loss of natural wetlands. One way to reduce this loss of habitat is to improve productivity of existing rice fields, e.g. in Western Africa (Tréca, 1992). In this region, since the early 1990s rice consumption has increased annually by an average of 4.6% and production only 3%, 2/3 of which being provided by expanding the cultivated area (Mendez del Villar and Bauer, 2013). After these authors, only 60% of the people's needs are fulfilled by local rice production. Annual yield in Western Africa remains very low, i.e. 1.5–2.1 t ha^{-1} compared to 4–6 t ha^{-1} in the inland-irrigated areas (Wymenga and Zwarts, 2010) or the world average of over 4.0 t ha^{-1} (Mendez del Villar and Bauer, 2013).

There could be a debate about whether some low productive areas should better be turned to wildlife-friendly habitats, and production be intensified in the already most productive ones, or wildlife-friendly practices should generally be implemented everywhere, even if this decreases overall yield. However, the ability to choose between these two options of course depends on whether or not local farmer populations are food-safe and how the land is owned.

Another possible solution to the problem of habitat loss is to restore abandoned rice fields to their natural wetland state. Such projects have been successful in different rice-growing regions, including in France (Mesléard et al., 1995), Spain (Comín et al., 2001), Japan (Kurechi, 2007) and Korea (Byun et al., 2008). All studies found that abandoned rice fields can be turned back to suitable habitat for native wetland plant communities within a few years, and can then be managed through control of hydrology and plant growth to provide attractive nocturnal feeding grounds (Mesléard et al., 1995) or roosting sites (Comín et al., 2001; Kurechi, 2007) for waterfowl. There is a high potential for such abandoned rice field restoration in Korea and in Japan, where government "set-aside" programs aimed at preventing over-production have yielded 160,000 ha and 54,000 ha of abandoned rice fields, respectively (Byun et al., 2008). Restoring wetlands in proximity to winter-flooded rice fields would provide both roosting and foraging grounds, optimizing the attractiveness of the area to waterfowl (Elphick, 2008; Buler et al., 2010).

4.1.3. Pesticide reduction and organic farming

Integrated Pest Management (IPM) schemes are regarded as a potential solution to the overuse or inappropriate use of pesticides by rice farmers. The concept of IPM was first applied to rice production systems at a large scale in Indonesia in 1989 (Röling and Van de Fliert, 1998). In the years that followed, 57 insecticides were banned in this country, the pesticide subsidy was eliminated, and the amount of rice pesticides consumed decreased by 65% (Parsons et al., 2010). Various educational programs have been launched throughout Asia to promote more sustainable agricultural practices on the small farm scale (Pontius et al., 2002). This has been successful in Vietnam, where over a three-year period IPM farmers reduced pesticide use by 65%, while non-IPM farmers increased pesticide use by 40% (Parsons et al., 2010). In general, integrated rice–duck or rice–fish farming systems have been reported to reduce chemical inputs onto the land by 50–65% (Parsons et al., 2010). In spite of this, agrochemical imports have continued to increase exponentially across Southeast Asia (Horgan, 2012).

Organic farming represents a small percentage of the world's riceland area, ranging from 0.1% in Africa to 5.1% in European Union (INRA, 2012). The organic-cultivated rice area has however increased by 138% between 2000 and 2010, now totalling 80,000 ha, mostly in Thailand (22,000 ha), USA (20,000 ha), Brazil (15,000 ha) and Italy (10,000 ha) (INRA, 2012). Organic farming could be promoted in Asia through the IRDF system development (Suh, 2014b). Few studies have compared the biodiversity of conventional versus organic-farmed rice fields, but those that exist have recurrently shown organic fields to host greater abundances of invertebrates, weeds, and more waterbirds than conventional fields (Tourenq et al., 2003; Mesléard et al., 2005; Ibáñez et al., 2010), however macro-scale drivers like climate and topography can also influence the benefits to biodiversity potentially attributed to organic farming (e.g. Amano et al., 2011), and should not be overlooked.

4.1.4. Reduction of sanitary problems

The best management practice to reduce the risk of pathogenic agent exchanges between farming ducks and wild waterfowl would be to better monitor the sanitary state of duck farming flocks, limit their movements, and increase farmers awareness of the disease (Men, 2010). For instance, heavy veterinarian surveillance helped to eliminate HPAI in Taiwan, Japan and South Korea (Gauthier-Clerc et al., 2007). Continuous flow of water through rice fields has also been suggested as a means to reduce the risk of disease outbreaks among waterfowl, though doing so may consequentially reduce invertebrate abundance (Elphick et al., 2010b).

4.1.5. Reduction of human disturbance, protection of rice fields

During the day most ducks roost in large extents of natural wetlands, areas which often receive some sort of legal protection. Nocturnal feeding on the other hand occurs mostly in unprotected areas. In the Camargue, southern France, 78% of these nocturnal grounds are private properties where duck hunting occurs mainly at dusk (Mathevet and Mesléard, 2002). Protecting some of these nocturnal feeding grounds, for instance flooded rice fields, could be an effective management option (Brochet et al., 2009b).

BirdLife International has identified 12,000 Important Bird and Biodiversity Areas (IBAs) worldwide, 40% of which now have some kind of official protected status (IBA, 2013). Although ricelands are considered the world's most important agricultural crop for waterbirds, they do not figure prominently among the waterfowl IBAs. There are however some examples of protected rice habitats across the globe, including in Europe (Ebro Delta, Spain, Ibáñez et al., 2010; Vercelli, Italy: Heath and Evans, 2000), America (Cuba: Acosta et al., 2010), Asia (Miyabayashi and Mundkur, 1999), Africa (e.g. Jakhaly rice-fields, Gambia, Doho Rice Scheme, Uganda, BirdLife International, 2014a,b). In California, 25% of rice fields are kept as sanctuaries for feeding and roosting waterfowl (National Wildlife Refuges, CVHJV Technical Committee, 1996 in Eadie et al., 2008). Reducing human disturbances in rice fields should promote their use by ducks, both as nocturnal foraging grounds and as day-roosts.

4.2. Promotion of the benefits

4.2.1. Waterfowl-friendly post-harvest agricultural practices

Owing to their migration patterns, non-sedentary ducks are most likely to use rice fields during the non-growing period. Since it is during this period that farmers face the fewest agronomic constraints, there exist many opportunities to introduce management practices aimed at conserving wildfowl. Many studies have investigated the influence of post-harvest practices on residual rice seed availability and accessibility to waterfowl (especially in the US, Japan and Europe, Elphick et al., 2010b), but few of these studies considered weed grains and invertebrates (Stafford et al., 2010). The amount of residual grain available to migratory birds at their winter quarters is reduced by the use of faster-growing rice varieties (Stafford et al., 2010), stripper-header harvesters (Stafford et al., 2006; Fleskes et al., 2012a) and ploughing (e.g. in US, Miller et al., 1989 in Stafford et al., 2010; in Japan, Lee et al., 2007 in Fujioka et al., 2010). The values of rice seed reduction by straw management is highly variable regionally (e.g. for the U.S. Eadie et al., 2008). For instance, Amano et al. (2006) reported that the amount of rice grains was reduced by 86.0% with field straw collection and by 95.2% with ploughing. While the extent to which straw management can influence the use of fields by ducks is unclear (Elphick et al., 2010b), dry-plowed fields are known to be avoided (Day and Colwell, 1998; Tajiri and Ohkawara, 2013), and burnt short straw flooded fields seem to facilitate easy forage of seeds on the ground (Havens et al., 2009) even if the absolute quantity of residual rice is reduced by approximately 30% (Miller et al., 1989 in Stafford et al., 2010). Methods that likely benefit both the farmers and ducks include flooding fields with stubble left standing post-harvest, doing incomplete burns post-harvest, and those minimizing mechanical treatment (Kross et al., 2008)—all of these post-harvest practices reduce labour and equipment costs while maximizing the waste rice available to waterfowl. More studies assessing duck foraging efficiency under various flooding and straw disposal treatments would be useful to better gauge the influence of the various post-harvest practices, notably in Europe.

Winter flooding of rice fields is the most popular duck-friendly post-rice harvest agricultural practice because it is relatively easy to implement, can provide agronomical benefits (e.g. straw disposal, weed control—see above and Table A.2), makes waste seeds more accessible to waterbirds, sometimes even producing new seeds and increasing further waterbird foraging opportunities (see ratoon crops above). Indeed, ducks are generally unable to handle seed food on dry land, and require water to increase their foraging efficiency and optimize use of available food sources (Guillemain et al., 1999). Some studies have investigated optimal water depth, suggesting that 14–22 cm was better for ducks, but that various depths within the riceland matrix could also benefit a variety of bird groups (e.g. Elphick and Oring, 2003). Other studies have shown how the timing and duration of flooding could be optimized to match duck migration episodes (Elphick et al., 2010b). Active winter flooding is becoming increasingly popular in some parts of the world (e.g. in the US, Eadie et al., 2008; Japan, Kurechi, 2007; Tajiri and Ohkawara, 2013 and Europe, Spain, Ibáñez et al., 2010; Toral et al., 2011), and passive flooding through rainwater retention is a low-cost procedure that could be employed in areas where flooding costs are too high (Japan, Shimada et al., 2000 and Europe, Lourenço and Piersma, 2009).

The flooding of rice fields during the non-growing season can be promoted in a variety of ways. Some successful examples from the last three decades include legislation (e.g., California Rice Straw Burning Act, 1991 in Anders et al., 2008), experimental tests at small scale (e.g CORINAT, 2010 in Italy, Ricefield Bird Study Group in South Korea, e.g. Choi and Yoo, 2014), activities of non-governmental organizations at the local scale (e.g. Wild Bird Society of Japan, Tajiri et al., 2014; Nature Conservancy in California, The Nature Conservancy, 2014), compensation measures (e.g. Migratory Bird Habitat Initiative after the Mexico Oil Spill, Marty et al., 2012), governmental incentives (e.g. European Life Project Ebro Delta Proyecto Life 96 NAT/E/3133, European Life Project ECORICE Vercelli Progetto Life09 NAT/IT/000093) and inter-governmental decision making (e.g. North American Waterfowl Management Plan, USFWS, 2014). Unfortunately, despite the increasing popularity of the technique, no authoritative guideline exists advising how to best implement winter flooding across the worlds diverse rice-growing landscapes.

4.2.2. The financial issue: how to get farmers enrolled in waterfowl-friendly management schemes?

In order for waterfowl-friendly practices to be broadly employed, the agronomic and conservation goals which are sometimes in conflict must first be reconciled. Although most waterfowl-friendly practices appear to be neutral to beneficial in agronomic terms, in some areas the idea remains that ducks are pests. The evidence indicates actual damages caused by ducks are for the most part rare and geographically restricted and have little impact on regional yields (West Africa excepted). Educating farmers in the intricacies of rice–duck interactions could instil in them the confidence to employ waterfowl-friendly practices, with agronomic and ecologic benefits to follow. Costs associated with winter flooding can be reduced through the optimization of the practice, for example by identifying and flooding not in excess of the optimal water depth (Eadie et al., 2008). If compensation is to be provided, giving priority to areas with high concentrations of waterfowl and requiring assurances that flooding coincides with the influx of migrants would ensure the efficient use of funds (e.g. BirdReturns Project, The Nature Conservancy, 2014). Similar schemes promoting the conservation of farmland birds have been successfully implemented in industries other than rice (e.g. Musters et al., 2001; Verhulst et al., 2007).

Some farmers already receive monetary incentives to keep water in their fields during the winter. In the US, farmers get $45 per acre flooded from the federal government (Eadie et al., 2008) and in one region of Japan farmers receive a grant of 800JPY minimum (equivalent US $67.54) per 10 acres for organic produced fields flooded during winter (Natuhara, 2013). In the Ebro Delta and Albufera de Valencia in Spain, rice farmers get around 60€ ha^{-1} (equivalent US $66.7 ha^{-1}) through agri-environment schemes to implement winter flooding (Albufera, Law: RD 4/2001 and RD 708/2002, Ebro Delta: Council Regulation (EC) No 1257/1999). Agri-environment schemes have proven to be especially effective in increasing the conservation value of rice habitat over large areas (Elphick et al., 2010a). Modern initiatives reduce costs by relying on reverse auction (BirdReturns Project, The Nature Conservancy, 2014) or by adjusting payments made to farmers according to the number of birds that actually benefit from such measures on their farms ("per clutch payment system", Musters et al., 2001).

Beyond the agronomic benefits that come from having ducks on rice fields (trampling of stubble, fertilizer inputs, weed control etc.), other avenues of revenue exist which stem from managing farms sympathetically for ducks. Marketing products as "waterfowl-friendly" could command a higher price in much the same way that organic or fair trade labels do (Spanish Ebro Delta organic rice, http://www.rietvell.com/, see also "CheolwanCrane Rice," in Korea, "Ibis Rice" in Cambodia, http://www.wildlifefriendlyorg/ibis-rice in Elphick et al., 2010a). Furthermore, the "consumption" of these birds by hunters, birdwatchers or ecotourists could also provide additional income to farmers by catering to tourists or selling hunting licenses (e.g. hunting: Grado et al., 2011, birdwatching: Kerlinger, 1993 in Eadie et al., 2008, environmental

education: SEO Birdlife Ebro Delta, Spain, http://www.rietvell.com/; Japan: Washitani, 2001).

5. Perpectives: the current issues and research needs

Unexpectedly, the biggest unknown remaining in our understanding of the wild duck–rice farming system is the extent to which rice fields are actually used by ducks. Though many surveys have attempted to measure this, most studies were conducted during daylight hours, missing entirely the nocturnal influx of foraging ducks (McNeil et al., 1992). As a result, bird densities and bird use remain poorly estimated (e.g. Tourenq et al., 2001a; Bellio et al., 2009; Taylor and Schultz, 2010; Guadagnin et al., 2012). It is absolutely crucial to better quantify the number of ducks coming to rice fields at dusk, a task which is becoming easier with the advancement of several technologies, such as light amplifiers (Pirot, 1981; Guillemain et al., 2002), radio-tracking (Cox and Afton, 1997; Fleskes et al., 2005), satellite tracking (Don Pablo Research Team, 2012), thermal cameras (Bywater et al., 2014) and weather radar (Buler et al., 2010).

Future research should be done to better understand the drivers behind the movements of waterfowl between natural and artificial wetlands, as well as between their day roosts and nocturnal foraging grounds—i.e., provide a better assessment of the effect of riceland landscape features and heterogeneity. Riceland landscapes are highly dynamic within and among years, and the matrix of favourable and unfavourable habitats for birds can change over a short time period (King et al., 2010). Birds are known to respond to spatial and temporal landscape heterogeneity in rice paddy areas (Amano, 2014), the response varying between species, due possibly to their habits and habitat preferences (Chan et al., 2007; Elphick, 2008). Key elements such as open water area (Chan et al., 2007), the amount of managed refuges, semi-natural wetlands (Elphick, 2008) or interspersed permanent wetlands (Pearse et al., 2012) all influence waterfowl community assemblages. Riceland habitat studies are necessary to implement landscape-scale conservation plans involving both wetlands and flooded agricultural land (King et al., 2010).

To create an effective management plan of a rice-growing region, one must have an idea of the potential carrying capacity of the rice fields in question. In order to accurately estimate this value, it is necessary to consider availability of all food sources (Stafford et al., 2010), the amount of energy and nutrition provided by these foods (Kaminski et al., 2003), and how that value might change throughout the winter (Nelms and Twedt, 1996). The actual foraging behaviour of the ducks in the fields also deserves more attention: their functional response has been experimentally quantified in a few cases (e.g. common teal feeding on rice, Arzel et al., 2007), but more research is necessary before expected Duck Use-Days can be accurately estimated (e.g. DUDs calculation considering depletion, Manley et al., 2004; Stafford et al., 2006; Greer et al., 2009). The impact of other granivores on available seeds in rice fields has not been thoroughly studied either. A study by Stafford et al. (2006) estimated 71% depletion in waste rice availability between harvest and late autumn in the MAV attributed to consumption by granivores, and to a lesser extent germination and decomposition.

One of the main results of the present literature review is that winter flooding of rice fields is a relatively easily implemented post-harvest practice which readily translates into increased habitat area for waterfowl. However, the longer-term consequences of the practice, for example how the yield of subsequent crops might be affected, remain poorly explored (see however Bird et al., 2002). Furthering our knowledge regarding such consequences would be helpful when evaluating the cost-benefit analysis of implementing winter flooding. The particulars about the flooding practice also remain uncertain, and further research into when best to flood, for how long to let water stand, and optimal water depth would be useful. Research into best practices has been done, thought, and some studies have attempted to determine whether short flash floods would be better than repeated pumping of water (e.g. Fleskes et al., 2012b), while others suggest the non-synchronized flooding instead of synchronized neighbouring fields flooding should be advised so that fresh seeds become gradually available to birds through the winter (Miller et al., 2010).

Ducks however do not constitute the whole bird community found among ricelands. If the presence of dry rice fields can mean a significant loss of habitat for ducks (Duncan et al., 1999), they may be readily used by other birds (e.g. hawks, harriers and kites, doves, larks, sparrows, finches, Elphick, 2004; cranes after pers. obs. by the authors). While positive for ducks, flooding of rice fields in winter may hence potentially have negative consequences for other birds (Elphick, 2004). Amano et al. (2008) demonstrated the importance of maintaining a combination of rice fields, open water, fallow fields and forests for sustaining a high diversity of birds in Japan. When determining best practices for flooding rice fields, it will be important to consider all resident and migrant avifauna of the region, not just duck populations (Amano et al., 2008).

The decision of how best to proceed with post-harvest ricefield management will be made easier by the use of modern bird distribution maps (eBird system (Sullivan et al., 2014) used for BirdReturns Project, The Nature Conservancy, 2014), and even more so by the recent development of energetic models (e.g. TRUEMET: Petrie et al., 2014) and multi-agent behaviour-based models, such as the Individual Based Model on foraging patterns of white-fronted geese (*Anser albifrons*) developed by Amano et al. (2006), or the spatially explicit model SWAMP (Miller et al., 2014). Such models help predict the movements and use of the fields by wintering ducks, and because they are energetic models where model bird decisions are based on expected energy acquisition from the possible fields, the precision of the output will be enhanced by the future foraging ecology research suggested above. In the future, such models should be broadened to include rice fields and surrounding areas, i.e. all of the territory used by ducks within a given region. In this way the complex habitat and nutritional requirements of ducks in ricelands, where agricultural, semi-natural and natural wetlands are all used, can be better assessed.

Before large-scale and effective management plans can be implemented, the involvement of the various stakeholders must be realized (see also Elphick et al., 2010a), as is the case in the US where such programs are built on tight collaboration with private farmers (e.g. Migratory Bird Habitat Initiative: Marty et al., 2012; California Migratory Bird Conservation Partnership, http://www.camigratorybirds.org/). Inviting rice farmers, hunters, and naturalists to take part in discussions or modelling exercises testing different ricefield management scenarios (e.g. through multi-agent models, Mathevet et al., 2003) will help identify their concerns and gather useful input pertaining to proposed practices and protected areas. For instance, modern funding procedures (e.g. reverse auctions, per clutch payment system) may also be easier to accept than more traditional agri-environmental subsidies. Moreover, consultation with these stakeholders will increase the likelihood of choosing an acceptable funding scheme, optimizing the use of funds and therefore the chances of the initiative being succeeding.

The ability of ricelands to provide foraging habitat for waterbirds in the future will depend largely on commodity prices, food security, global and regional economics, water availability, management practices, and the area of cultivated land. The agronomic and ornithological worlds should pursue more frequent and open lines of communication to fully account for the costs and benefits of conservation initiatives and duck–rice farming, thereby

getting a better idea of the economic viability of different management practices. Relatively simple measures can be taken to improve the usability of these habitats to waterfowl, the farmers in turn benefitting from the services coming from having these animals on their farms (Green and Elmberg, 2014). As opposed to some other agricultural systems, the present literature review suggests that wild duck–rice farming is a mutually beneficial association, and one that could be enhanced by the results of future research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.08.018.

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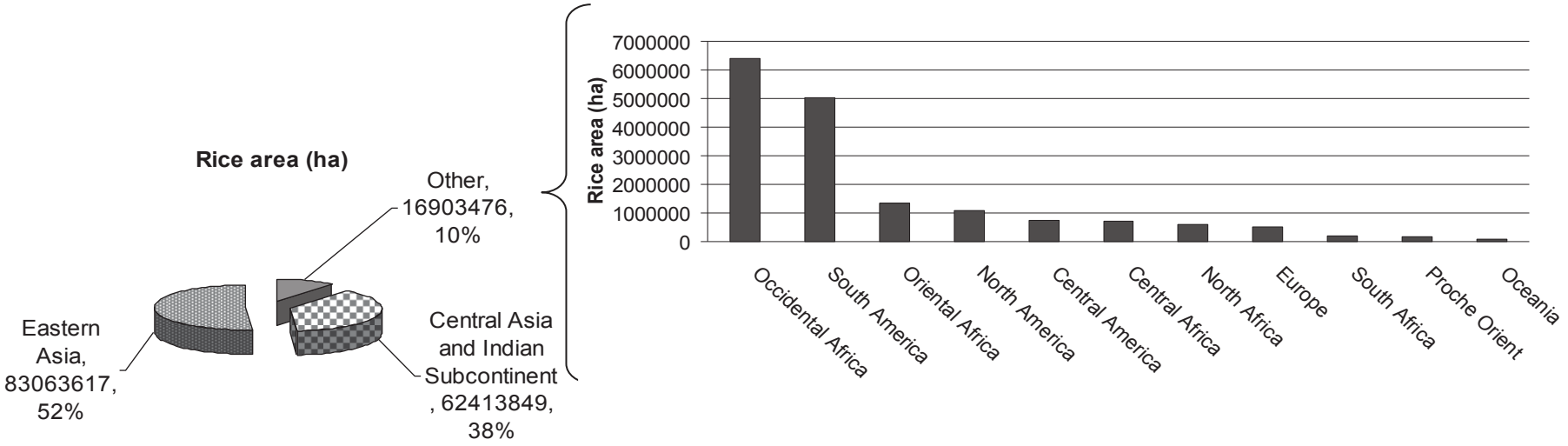
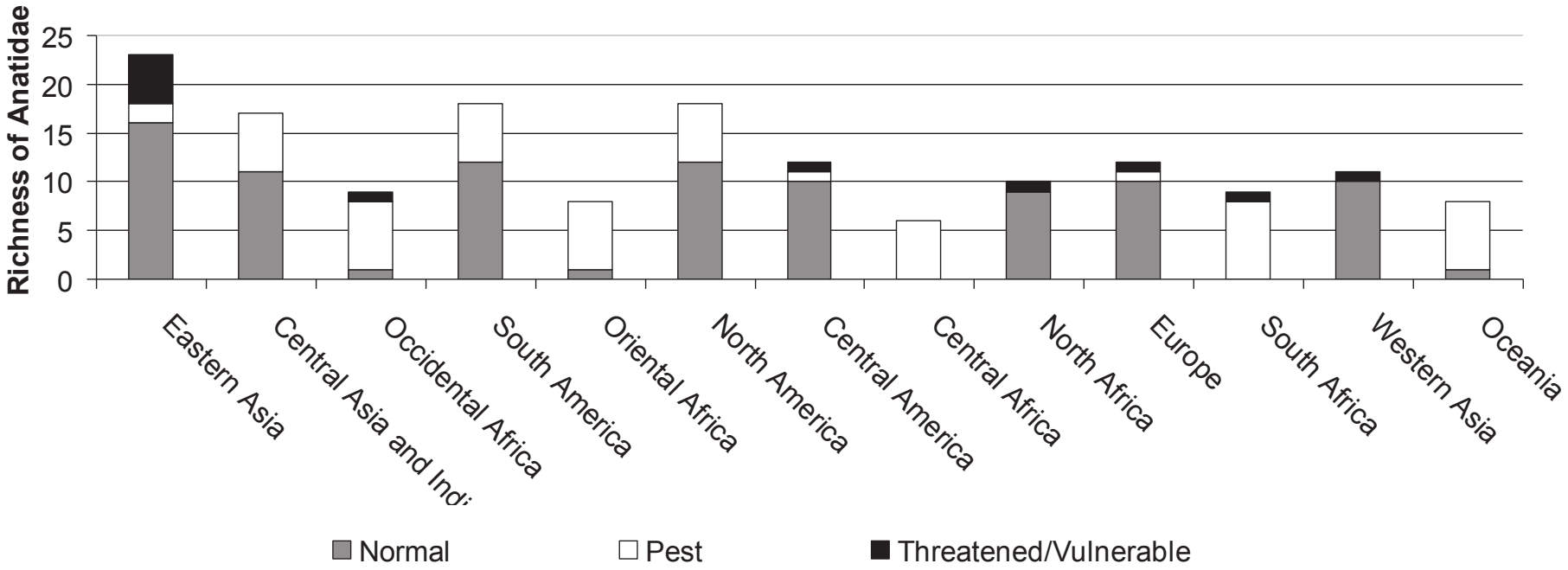
SUPPLEMENTARY INFORMATION: Article 1

Figure A.1. Rice cover (ha) in the main production areas in year 2011 (data after FAO-STAT, 2013).



SUPPLEMENTARY INFORMATION: Article 1

Figure A.2. Number of Anatidae species that use rice fields in the main geographic areas (after Elphick et al., 2010a). The number of pest, threatened or vulnerable species is differentiated (IUCN, 2014). Geographic distributions after: Madge and Burn, 1995; Critical Site Network Tool, 2014.



SUPPLEMENTARY INFORMATION: Article 1

Table A.1 Duck species that have been classified as rice pest in the literature.

Species	Country/Region	References
White-faced Whistling Duck *Dendrocygna viduata*	South Africa Tanzania Senegal, Mali Cameroon Argentina, Colombia, Nicaragua, Surinam, Uruguay, and Venezuela	Petrie and Petrie, 1998 in Kear, 2005 Katondo, 1996 Tréca, 1992 De Grazio, 1978 De Grazio and Besser, 1970 in de Grazio, 1978
Fulvous Whistling Duck *D. bicolor*	Louisiana, Florida, and Texas, USA Venezuela Argentina Cameroon	Mugica, 1993; Hohman et al., 1996 Flincklinger and King, 1972 in Stafford et al., 2010 Meanley and Meanley, 1959 in Czech and Parsons, 2002 Bruzual and Bruzual, 1983 Gomez-Dallmeier and Cringan, 1990 in Kear et al, 2005 Ferreyra et al., 2009 De Grazio, 1978
Lesser Whistling Duck *D. javanica*	South Asia	Ali and Ripley, 1987 in Sundar and Subramanya, 2010
Black-bellied Whistling Duck *D. autumnalis*	Guyana	Bourne, 1981
Whistling tree duck *D. arcuata*	New Guinea	Grist and Lever, 1969 in de Grazio, 1978
Spotted tree duck *D. guttata*	New Guinea	Grist and Lever, 1969 in de Grazio, 1978
Mallard *Anas platarhynchos*	South Asia/Japan Bulgaria USA	Sundar and Subramanya, 2010; Lane, 1998 Grist and Lever, 1969 in de Grazio, 1978 Phillips, 1923
Northern Pintail *A. acuta*	South Asia Senegal/Mali USA	Sundar and Subramanya, 2010 Tréca, 1992 Phillips, 1923
Garganey *A. querquedula*	South Asia, India Senegal/Mali	Sundar and Subramanya, 2010 Hume and Marshall, 1879 in Phillips, 1923 Tréca, 1981 in Tréca, 1992

Indian Spot-billed Duck *A. poecilorhyncha*	South Asia Japan, China, India, Pakistan	Sundar and Subramanya, 2010 Lane, 1998
Gadwall *A. stepera*	South Asia	Sundar and Subramanya, 2010
Red-billed duck *A. erythrorhyncha*	Tanzania Madagascar	Katondo, 1996 Roch and Newton, 1863 in Phillips, 1923
Blue-winged Teal *A. discors*	Suriname, Guyana Arkansas, USA	Grist and Lever, 1969 in de Grazio, 1978 Phillips, 1923
Yellow-billed Pintail *A. georgica*	Argentina	De Grazio, 1978 Ferreyra et al., 2009
Mottled Duck *A. fulvigula*	Arkansas, USA	McAtee, 1918 in Phillips, 1923
Grey Teal *A. gracilis*	Australia	Taylor and Schultz, 2010
Pacific Black Duck *A. superciliosa*	New Guinea, New South Wales	Grist and Lever, 1969 in de Grazio, 1978
Gray Teal *A. giberrifrons*	New South Wales, Australia	Grist and Lever, 1969 in de Grazio, 1978
Knob-billed Duck *Sarkidiornis melanotos*	South Asia Tanzania Senegal	Sundar and Subramanya, 2010 Katondo, 1996 Tréca, 1992
Wood Duck *Aix sponsa*	MAV, USA	Stafford et al., 2010
Rosy-billed Pochards *Netta peposaca*	Argentina	Ferreyra et al., 2009
Brazilian Teal *Amazonetta brasiliensis*	Brazil	Ferreyra et al., 2009
Maned Duck *Chenotta jubata*	New South Wales, Australia	Grist and Lever, 1969 in de Grazio, 1978

SUPPLEMENTARY INFORMATION: Article 1

Table A.2 Agronomic benefits of winter flooding and foraging by wild or farm ducks. Read also Long et al. (2013) for more details.

Agronomic variable	Treatment	Results	Localisation, Source
Straw decomposition	Winter flooding	Straw biomass decreased 43-68%	MAV, Manley et al., 2005
	Winter flooding +Wild Waterfowl	Straw decomposition in flooded fields with waterfowl more than twice greater	California, Van Groenigen et al., 2003
		Straw biomass decreased 27-41% in flooded fields, 72-76% in flooded fields with waterfowl	California, Bird et al., 2000
		Stalks reduction increased with duck densities	France, Brogi et al., 2015
Nutrient cycling/ Nutrient conservation/ Water quality	Winter Flooding	Crop N uptake increased 26%	California, Eagle et al., 2001 in Anders et al., 2008
		Soil and nutrients conservation, runoff water quality improved	MAV, Manley, 1999 in Anders et al., 2008
	Wild Waterfowl	Residual 15N decreased 83%-89%	California, Van Diepen et al., 2004
	Rice-duck farming	Return of C, N and P into paddy soils increased by 20%, 56% and 379%	China, Fan, 2012
		Total N, P and K increased 85-506%, 201-870% and 43-109%	China, Quan et al., 2008
		Soil organic matter, total N, available N, P and K increased 11-29%, 3-15%, 6-10%, 4-10% and 23-27%	China, Zhi-hui et al., 2004
Greenhouse gasses: CH_4/N_2O	Rice-duck farming	CH_4 emissions 6.7% lower when chemical fertilizer used together with ducks	China, Zhang et al., 2011
		CH_4 reduced 19.3-19.6%	China, Zhan et al., 2011
		CH_4 emissions of no-tillage areas with ducks 25% lower than without ducks, and 40.5% lower than conventional-tillage areas without ducks	China, Xiang et al., 2006

		CH_4 emissions decreased by 44.2% for early rice and 40.7% for late rice	China, Huang et al., 2003
		Lower N_20 emission rates and 22% lower global warming potential in fields with ducks and organic fertilizers than fields with ducks and chemical fertilizers	China, Zhang et al., 2008
		Nitrogen leakage reduced 5-7% by the presence of fish and ducks in rice paddies; N_2O emissions lower in fields with ducks (51.4 kg $N.ha^{-1}$) and fish (52.6 kg $N.ha^{-1}$) than conventional fields (55 kg $N.ha^{-1}$)	China, Cheng-fang et al., 2008
Weed seeds	Winter flooding	Weed biomass reduced 24-83%	Mississippi, Manley et al., 2005
	Wild Waterfowl	Growing season weed biomass decreased > 50% following a winter with ducks in flooded rice fields	California, Van Groenigen et al., 2003
	Rice-duck farming	Weed biomass reduced 84% after farm duck trampling and 98% after farm duck trampling + grazing	China, Zhang et al., 2009
		Weeds decreased 68% and 98% after 15 and 45 days of duck release	China, Yu et al., 2008
		Weed growth reduced 96% and weed variety decreased	China, Zhen et al., 2007
		Weed vegetation reduced up to 90%	Bangladesh, Hossain et al., 2005
		Weeds reduced 99%	China, Yu et al., 2004
		Weed biomass reduced 52-58%	Philippines, Cagauan, 1997
Weedy rice *Oryza sativa*	Winter flooding/Freezing	Weedy rice seed viability 90% in unflooded paddies, 61% in flooded paddies, 78% after freezing treatment	Korea, Baek and Chung, 2012
	Winter flooding	Weedy rice seed viability at the end of winter reduced by 95% in flooded fields, 26-77% in unflooded fields	Italy, Fogliatto et al., 2010
Red rice *Oryza punctata/peren*	Winter flooding	Red rice + other weed infestations reduced	USA, Street and Bollich, 2003

nis	Waterfowl	Red rice seeds decreased 97% in fields heavily infested with red rice and adjacent to a wildlife area with large numbers of ducks	Arkansas, Smith and Sullivan, 1980
	Dendrocygna viduata	White-faced Whistling Duck foraged for *Oryza perennis* and *Cyperus rotundus*	Venezuela, Bruzual and Bruzual, 1983 in Kear, 2005
	Anas fulvigula	Mottled Duck found to consume red rice	Arkansas, McAtee, 1918 in Phillips, 1923
Barnyard grass /Millet *Echinochloa* spp.	*Anas platyrhynchos*	Rice, *Echinochloa crus-galli,* and *Glyceria declinata* consumed by wintering mallard	Portugal, Rodrigues and Ferreira, 1993 Rodrigues et al., 2002
		11% of total volume of seeds eaten by Mallards, third most consumed seed after rice and acorns	Arkansas, Forsyth, 1965
		17% of total volume of seeds consumed by Mallards, second after rice	Arkansas, Wright, 1959
	Anas platyrhynchos/ *Anas crecca*	Rice, *Echinochloa sp*., *Scirpus maritimus,* and *Potamogeton pusillus* seeds four most important food items in diet of Mallard and Teal	France, Brochet et al., 2012
	Dendrocygna autumnalis	Millet, *Echinochloa* sp. and *Paspalum* sp. most important food items to Black-bellied Whistling Duck after rice	Guyana, Bourne, 1981
	Dendrocygna bicolor	Aquatic earthworms *Oligochaeta* and wild millet seeds *Echinochloa* sp. most important food items for Fulvous whistling ducks	Louisiana, Hohman et al., 1996
	Rice-duck farming	Young millet controlled by foraging farming ducks during early summer	Japan, Tojo et al., 2007
Algae/Aquatic organisms	Rice-duck farming	Algae and aquatic animal biomasses reduced, increased biodiversity index value	China, Wang et al., 2006
Invertebrates	Rice-duck farming	Number of arthropod individuals and biodiversity index values higher	China, Zhong et al., 2011
		Diversity of aquatic organisms lower	Japan, Yamazaki et al., 2004

Golden apple snail *Pomacea canaliculata*	Rice-duck farming	Golden apple snail density reduced > 80%	Japan, Teo, 2001
	Anas platyrhynchos	Predator of apple snail	Japan, Yusa et al., 2006
Planthopper and leafhopper	Rice-duck farming	Brown planthopper outbreaks controlled by altering its spatial distribution patterns and ecological niche characteristics + those of its natural enemies	China, Qin et al., 2011
		Number of planthopper and leafhopper decreased 65% 12 days after ducks released, 79% after 42 days	China, Yu et al., 2008
		Leafhopper, planthopper and rice bug populations significantly lower	Bangladesh, Hossain et al., 2005
Rice blast disease	Rice-duck farming	Diseased hill rate, diseased plant rate and disease index of rice sheath blight better controlled by rice-duck farming than by treatment with pesticides	China, Xue et al., 2009
		Rice blast controlled, 57% of outbreaks prevented	China, Zhen et al., 2007

SUPPLEMENTARY INFORMATION: Article 1

Table A.3 Duck species known to breed in ricelands.

Species	Country/Region	References
Fulvous Whistling Duck *Dendrocygna bicolor*	Louisiana, USA Cuba Argentina and Brazil	Hohman et al., 1996 Mugica, 1993 in Pierluissi, 2010 Don Pablo Ranch Project, 2012
Black-bellied Whistling Duck *D. autumnalis*	South Texas, USA Guyana	Bourne, 1981
Lesser Whistling Duck *D. javanica*	India	Sundar and Subramanya, 2010
West Indian Whistling Duck *D. arborea*	Cuba	Acosta et al., 2010
Mallard *Anas platyrhynchos*	California, USA Italy	McLandress et al., 1996 in Pierluissi, 2010 Fasola and Ruiz, 1996
Cinnamon Teal *A. cyanoptera*	California, USA	Taft and Elphick, 2007
Mottled Duck *A. fulvigula*	Louisiana, USA	Durham and Afton, 2003 in Pierluissi, 2010
Indian Spot-billed Duck *A. poecilorhyncha*	Japan	Fujioka et al., 2010
Pacific Black Duck *A. superciliosa*	Australia	Taylor and Schultz, 2010
Common Shelduck *Tadorna tadorna*	Europe	Longoni, 2010
Red-crested Pochard *Netta rufina*	Europe	Longoni, 2010
Rosy-Billed Pochard *N. peposaca*	Argentina and Brazil	Don Pablo Ranch Project, 2012

CHAPTER II. INFLUENCE OF POST-HARVEST PRACTICES ON SEED AVAILABILITY AND DUCK USE

Different post-harvest practices, Claire Pernollet

II.1 Background information

This second chapter considers the influence of agronomic management procedures, especially the means of straw disposal, on wintering waterfowl conservation. It aims at determining the most suitable post-harvest agricultural practices in rice fields for providing foraging habitat to wintering ducks in Europe by assessing seed **resource availability** as well as **duck use** through direct and indirect estimates of duck abundance (**Figure 6**).

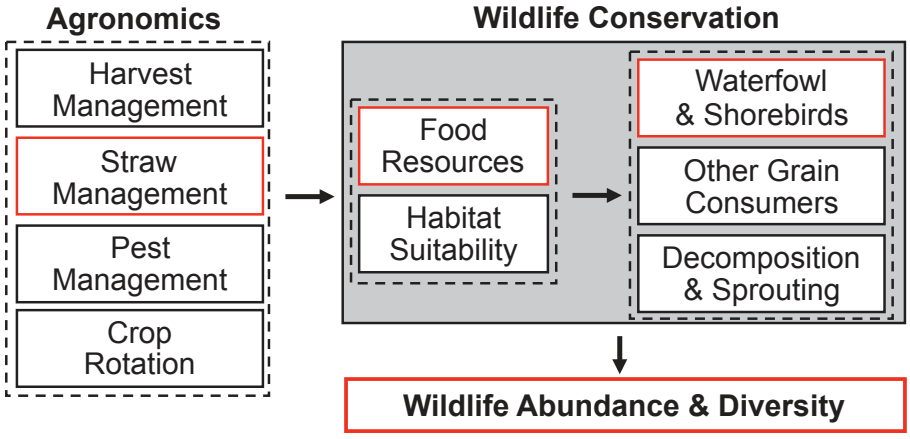


Figure 6. Integration of agronomic values and wildlife conservation in ricelands. Only links from agronomy to wildlife conservation have been kept from the initial framework (reproduced from Eadie et al. 2008, with kind permission from S. Manley). In red colour the elements that were studied in this chapter.

We particularly focused on winter flooding, identified in **Chapter I (Article 1)** as the best waterfowl-friendly management procedure in harvested rice fields. We estimated the extent to which such practice is used at the European flyway scale **(Article 2),** and then evaluated its consequences for ducks through empirical studies in the French rice production area (Camargue) **(Article 3).**

We first assessed the importance of coarse landscape factors (i.e. wetland habitat types) in explaining the number of wintering ducks in five rice-growing regions of Spain, France and Italy **(Article 2)**. Seed availability and nocturnal duck use of rice fields submitted to a diversity of straw management procedures were then measured specifically in southern France (Camargue) (**Article 3)**.

Historical studies in the 80's and the 90's monitored food resources availability and nocturnal duck frequentation in flooded rice fields, fallow rice fields and natural shallow wetlands in Camargue (Tamisier and Dehorter, 1999; Pirot, 1981; Mesléard et al., 1995). They suggested that flooded rice fields represented an important foraging habitat for granivorous ducks, which frequently visited those natural and artificial wetlands. These results were reviewed in Tamisier and Dehorter (1999) and then compared with the data from other Italian and Spanish rice production regions in Mañosa i Rifé (1997), which constituted the basic historical information for developing the questions of **Chapter II (Articles 2, 3)**. As opposed to these former authors, Tourenq (2000) conversely concluded that a mere 6% of the Camargue rice fields were flooded during winter (as opposed to ca. 10% in Pirot, 1981) and were not a major habitat for ducks, while Pirot (1981) estimated that these hosted 40% of the Camargue granivorous duck population. Updating of the estimation of winter flooding and duck use of flooded fields was therefore required to better understand the system.

II.2 Key messages and supporting evidence

The studies presented in the articles of this chapter provided new evidence which may benefit wetland and waterbird conservation, as they allowed:

1/ to get an updated evaluation of the conservation importance of major European rice production areas for waterfowl, and the contribution of ricefield winter flooding to such importance.

An estimated 80-90% of the natural wetlands in the Mediterranean region have been lost, and ca. 23% of the remaining wetlands are artificial (Finlayson et al., 1992; Perennou et al., 2012, respectively).

The five study regions present much contrasted landscapes in terms of wetland/rice ratios, ranging from 1 to 75%. Post-harvest practices also greatly differ, with 0.17 to 62% of the rice fields getting flooded during winter. In Camargue, the 9% of rice fields that are flooded get so for hunting purposes. The use of winter flooding varies considerably depending on the implementation of this practice through a "Winter Flooding" Agri-Environmental Scheme (AES). The results show that mean dabbling duck numbers were positively correlated with wetland area in the broad sense, i.e. natural wetlands plus winter flooded ricefield areas **(Article 2)**.

2/ to reopen the debate on complementarities between wetlands and rice fields.

Most studies aiming at determining if rice fields could be valuable substitutes or complements to natural wetlands in terms of waterbird conservation considered the diurnal bird communities, and came to different conclusions (e.g. Fasola and Ruiz, 1996; Toral and Figuerola, 2010 *versus* Tourenq et al., 2001; Bellio et al., 2009). However, the importance of such potential complementary can be underestimated by diurnal censuses, since many species such as ducks and waders using fishponds or marshes as daily refuges only commute to the rice fields for foraging at night (Toral et al., 2011). Therefore, surveys conducted in rice fields during daylight hours may entirely miss the nocturnal influx of foraging birds (McNeil et al., 1992; Martin, 2010). The results of **Article 2** and those from the nocturnal duck surveys in Camargue in **Article 3 do highlight the complementarities between natural wetlands and rice fields**.

In Camargue, while most of the major duck day roosts are clearly identified and receive some degree of protection, the provision of more nocturnal foraging grounds and a better protection of some of these have now been identified as priorities for conservation (Brochet et al., 2009). The way birds disperse from their main day-roosts to rice fields for nocturnal foraging purposes may greatly differ between winter quarters (**Figure 7**), owing to both the structure of the habitat matrix and the behavioural strategies of the birds.

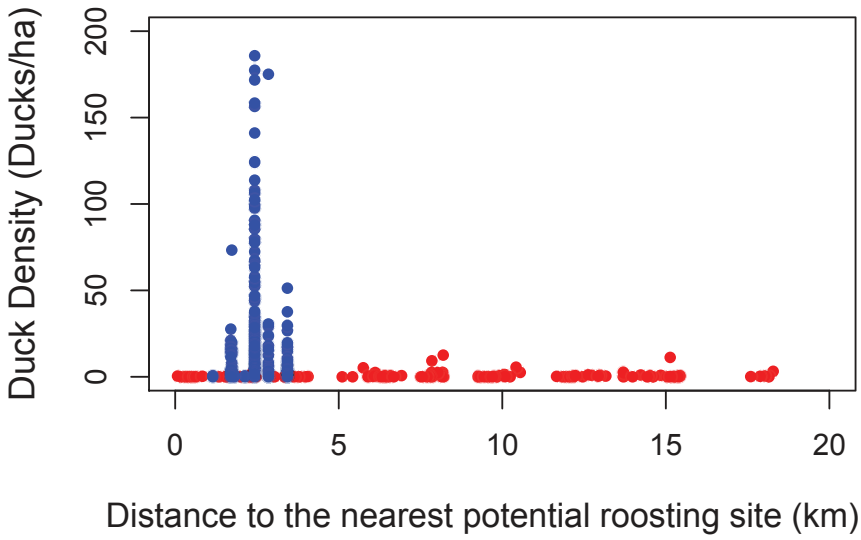


Figure 7. Nocturnal duck densities in rice fields as a function of distance to the nearest potential roosting site in Camargue (France, blue dots) and in Doñana (Spain, red dots). Extracted from Appendix II.2.

Studying the spatial organisation of the natural wetlands with deeper waters (used as day-roosts) and shallow foraging habitats including flooded rice fields is therefore crucial, as this could profoundly affect the nocturnal movement patterns of the birds and hence the energetic costs to access to food resources (refer to the description of the modeling SWAMP **project in the Discussion**).

3/ to estimate seed availability in French post-harvest rice fields and how it changes with post-harvest practices and across the winter.

An average of half a ton of seeds were available after harvest in the first 5 cm of ca. 50 French rice fields sampled during the winters of 2012-2013 and 2013-2014 (rice: 349.9 kg/ha ± 57.6 SE; weed seeds: 141.6 kg/ha ± 21.3 SE). The abundance of this food resource was highly variable among and between fields, and was not dependent on initial straw management procedures (burning, chopping or disking). Average rice density however subsequently decreased by 89% and weed seed density by 69% between post-harvest and late winter. Seed depletion rate was highly dependent on initial seed density, and was greatest in ploughed fields **(Article 3)**. We advise landowners to refrain from winter ploughing or to delay it as long as possible, as this activity greatly reduces seed forage available to wintering birds.

4/ to examine the influence of ricefield management practices on bird use: the best for ducks, the best for the rest of the community?

Articles 2 and 3 reach the same conclusion that winter flooding is the main driver of duck presence in rice fields. Wintering duck abundance was greater in regions with more rice fields flooded after harvest, i.e. providing more potential nocturnal foraging grounds (**Article 2**). Comparing the actual bird densities within the harvested rice fields of a given region (Camargue), the importance of flooding for nocturnal duck use has been demonstrated, since 23.5 ducks were recorded per hectare of flooded field (± 2.3 SE), versus 0.3 in unflooded fields (± 0.1 SE) (**Article 3).**

In our study in Camargue, duck numbers were greatest in fields under 5-10 cm of water, which corresponds to the preferred foraging depths and postures of these birds as they likely allow greater foraging efficiency (e.g. Guillemain et al., 2002a, 2002b). With an average of ca. 6 cm between October and February (PNRC, 2013b), Camargue rainfall alone could provide the minimum suitable depth for dabbling ducks if farmers simply closed field water gates after harvest **(Article 3)**.

Except for soil ploughing that should be avoided because it greatly reduces seed availability (e.g. in US, Miller et al., 1989 in Stafford et al., 2010; in Japan, Lee et al., 2007 in Fujioka et al., 2010, **Article 3**), no clear effect of post-harvest management on seed availability and duck use was detected as long as water covered the fields, suggesting that any flooded non-ploughing agricultural management would be suitable to wintering waterfowl.

5/ to test the effectiveness of the ricefield "Winter Flooding" Agri-Environmental Scheme and consider its implementation at the European flyway scale.

In Europe, environment-friendly practices are supported by Agri-Environment Schemes (AES) implemented through the Common Agricultural Policy. The European Community often lacks the factual data necessary to implement these recommendations, as well as scientific assessment of the efficiency of current schemes. AES have been implemented in Spanish ricefield areas at the beginning of the 2000s to promote winter flooding (Albufera, Law: RD 4/2001 and RD 708/2002, Ebro Delta: Council Regulation (EC) No 1257/1999), and **Article 2** proves that such AES have positively influenced duck population trends. Promoting such schemes more widely across the European rice production areas could make a big difference in terms of waterfowl habitat quality at the scale of their wintering range, as was done for instance in California.

Collectively, the articles of **Chapter II** therefore show that waterfowl conservation would greatly benefit from a wider implementation of winter flooding of harvested rice fields, with potential consequences ranging from a changed nocturnal distribution of the birds locally to a broader redistribution at the flyway scale. The next chapter in turn considers the possible agronomic consequences of winter use of the flooded fields by ducks from the point of view of the rice farmers.

Article 2:

A comparison of wintering duck numbers among European rice production areas with contrasting flooding regimes

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A comparison of wintering duck numbers among European rice production areas with contrasting flooding regimes

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ABSTRACT

Agricultural lands can provide suitable habitat for birds under some conditions. In particular, waterfowl sometimes rely on ricefields as nocturnal foraging habitat during winter if post-harvest practices make food accessible. To assess whether the winter flooding of ricefields could be a major driver of duck regional abundance in Europe, we relied on a combination of spatial and temporal analyses. In the former, five of the most important western European rice growing regions in Spain, Italy and France were compared in terms of habitat composition over the 2002–2012 period. The relative importance of natural wetlands and ricefields (either dry or flooded) in determining the abundance of wintering ducks was then established. In the second approach, the trends in duck numbers before and after implementation of winter-flooding Agri-Environment Schemes (AES) were compared in two of the study regions. Both approaches highlighted the role of winter ricefield flooding in explaining wintering duck numbers and complementing the natural wetlands; flooding harvested ricefields improves habitat attractiveness by enhancing food resource accessibility. In Europe, the proportion of ricefields flooded during winter varies considerably between countries (0.17–62%), owing to differences in policy initiatives such as Agri-Environment Schemes. Promoting such schemes more widely across the European rice production area could make a big difference in terms of waterfowl habitat quality at the scale of their wintering range.
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1. Introduction

Historically, conservation biology was largely oriented to preserving wilderness in remaining natural environments (e.g. Leopold, 1949). Since the 1980s, however, there has been growing interest in the improvement of anthropized landscape matrices, such as agricultural lands, as these represent a growing proportion of the environment in areas with intensive agriculture (Balmford et al., 2012). The two approaches have now been shown to be complementary in mitigating erosion of biodiversity and biotic interactions, and many studies have commented on the respective roles of natural and artificial wetlands for waterbird conservation (e.g. Fasola and Ruiz, 1996; Elphick, 2000; Toral and Figuerola, 2010 versus Tourenq et al., 2001a; Bellio et al., 2009; Taylor and Schultz, 2010; Guadagnin et al., 2012). Such questions have been recurrently raised around the Mediterranean region, one of the first 25 Global Biodiversity Hotspots (Myers et al., 2000) but also one of the regions where natural habitats have been transformed by human activities for the longest period. In the Mediterranean region an estimated 80–90% of former natural wetlands have disappeared (Finlayson et al., 1992), and ca. 23% of the remaining wetlands are artificial (e.g. ricefields, salt pans, irrigation reservoirs; Perennou et al., 2012).

Ricefields are one of the most important of these artificial habitats, and currently represent 15% of the world's wetlands (Lawler, 2001). Around the Mediterranean, in the European Union, rice is cultivated on a total of ca. 460,000 ha, the top producers being Italy (53%), Spain (24%), Portugal (7%), Greece (6%) and France (4%) (FAOSTAT, 2012).

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Although the expansion of ricefields is sometimes at the expense of natural wetlands, these fields have proven to be of general interest to a wide variety of waterbirds worldwide (see Elphick et al., 2010a), notably in Europe (Longoni, 2010). According to Toral and Figuerola (2010), ricefields represent one third of the suitable waterbird habitat in southern Europe (Italy, Spain, Greece, and Portugal).

The role of ricefields as winter diurnal roosts and feeding grounds for ducks is widely recognized in North America (Eadie et al., 2008), and more recently in Japan (Kurechi, 2007), where such habitats are managed in a waterfowl-friendly way. In Europe, ducks mainly gather during the day on natural or semi-natural deep wetlands (day-roosts), and only move at night towards distinct shallow water foraging grounds, including ricefields (well studied in the Camargue, France, see Tamisier and Dehorter, 1999). Due to such nocturnal behaviour, the use of ricefields by European ducks is difficult to quantify (Tourenq et al., 2001a), and is virtually unstudied in some regions. Thus, it is still unclear if ricefields can be considered valuable substitutes or complements to natural wetlands for wintering dabbling ducks in Europe.

Whether ricefields are attractive and provide abundant food resources to waterbirds may greatly depend on agricultural practices during the crop growing season (e.g. seeding practices, agro-chemical use and harvest method, Ibáñez et al., 2010) as well as during the post-harvest period (e.g. straw management such as crushing or burning, soil mechanical work such as mowing or disking, winter flooding and their combinations, Elphick et al., 2010b). In Europe, environment-friendly practices are supported by Agri-Environment Schemes (AES hereafter) contracted by farmers and implemented through the Common Agricultural Policy (CAP) (EC Directorate General for Agriculture and Rural Development, 2005). However, recommended practices can vary from one region to another as the final decision of which AES to implement is taken at the regional scale. Moreover, the European Community often lacks the data necessary to implement these recommendations, and scientific assessment of the efficiency of current schemes is also needed (e.g. Tourenq et al., 2001b; Ernoul et al., 2013).

One of the post-harvest management practices for which some European rice producers (mostly in Spain) receive financial support through AES is winter flooding of fields for several months. Winter flooding is largely practiced around the world, mainly promoted for waterbird habitat creation and hunting purposes, as well as straw decomposition and other environmental or agronomical benefits (e.g. North America: Eadie et al., 2008; Anders et al., 2008; Japan: Kurechi, 2007; Tajiri and Ohkawara, 2013). Previous studies showing how ricefield flooding can improve habitat quality for waterbirds have been restricted to those two countries. Some site-specific case studies exist in Europe (e.g. Tourenq et al., 2001a; Toral and Figuerola, 2010). However, no comprehensive study has been carried out in several sites in Europe to determine how such management is practiced at the flyway scale, and whether this can be a major driver of waterbird abundance at the regional scale. The extent to which this could potentially affect general population trends at the flyway scale in Europe has not yet been evaluated.

Local nocturnal surveys in the Camargue, southern France, have highlighted the great potential of flooded harvested ricefields to act as duck foraging grounds, since an average of 5–33 ducks/ha was recorded in flooded fields vs. 0.14 ducks/ha in dry paddies (C.A. Pernollet et al., unpublished data, see also Pirot, 1981). The aim of the present study was to go beyond this local information and assess whether winter flooding of European ricefields provides a suitable habitat for ducks, and thus translates into greater duck numbers at the regional scale. We first relied on a spatial analysis comparing five of the most important western European rice production areas in terms of habitat composition, and tried to establish the relative importance of natural wetlands and ricefields in determining the abundance of wintering ducks. Among ricefields a distinction was made between dry and winter-flooded fields, to accurately assess the effect of post-harvest management of ricefields, especially flooding, on duck abundance and species richness among the six dabbling duck species potentially using such habitats during winter. The second part of the study relied on a temporal analysis in two of the study regions, where winter flooding was introduced as an AES. There, the assessment of the link between agricultural policies and duck populations was conducted by comparing the trends in duck numbers before and after AES implementation, to test whether this led to more positive trends during later years.

2. Material and methods

2.1. Study regions

The study was carried out in five major European rice growing regions in Spain, France and Italy (Fig. 1). These regions were selected because they all belong to the same duck flyway (see flyway delineations in Scott and Rose, 1996), their ricefields were established on former natural wetlands, and their landscape has remained relatively stable over the last decade due to strong anthropological control of the hydrological system.

In Italy, rice farming is concentrated in the inland plain of the Po Valley, where it has been practiced since the 15th century. Our study focused on the province of Vercelli in Piedmont (45°19′N 08°25′E, ca. 208,000 ha of which 72,000 ha are cultivated with rice, average 2002–2012) and the province of Pavia in Lombardy (45°11′N 09°09′E, ca. 300,000 ha of which 81,000 ha are ricefields, average 2002–2012). In northwest Italy the climate is continental temperate, with cold winters and warm summers allowing culture rotations such as rice-maize-soybean/wheat or rice in conjunction with poplars or forage pastures (Mañosa i Rifé, 1997).

In France, rice production is restricted to the Camargue Rhône Delta, in the south of the country (43°30′N, 04°30′E), where it was introduced in 1942. This region of about 145,000 ha comprises 60,000 ha of natural and semi-natural wetlands and about 18,000 ha of rice (details in Tamisier and Dehorter, 1999). The climate of the Camargue is typically Mediterranean. This, combined with saline soils, restricts agricultural crops to either rice monoculture or rice–wheat-alfalfa rotation (Barbier and Mouret, 1992). As in Italy, French ricefields are dried out at the end of the growing season to facilitate harvest (July–August in Italy, September–October in France) and are mostly ploughed or disked during the winter depending on weather conditions (Mañosa i Rifé, 1997). The small flooded area during winter is mostly inundated for waterfowl hunting purposes.

The last two study regions are located in Spain along the Mediterranean coast: the Ebro Delta (40°42′N 0°43′E), where 21,000 ha of the total 32,000 ha of the area are covered with ricefields (details in Curcó and Bigas, 2012), and Albufera de Valencia (39°27′N, 0°13′E) where ricefields represent ca. 15,000 ha of the total 21,000 ha (details in Oltra et al., 2001). Rice cultivation was introduced at a large scale to both areas around 1860 (Mañosa i Rifé, 1997). The climate and soil conditions make rice the only crop in the lowlands of the Ebro Delta and Albufera de Valencia. Ricefields there remain flooded for a longer period, i.e. harvest is conducted in water and fields are only dried by the end of January, even sometimes later in hunted ricefields. The AES "ricefield winter-flooding" consists of maintaining the ricefield surface under flooding for at least 3.5 months in Albufera de Valencia (Law: RD 4/2001 and RD 708/2002) and at least 4 months in the Ebro Delta (Council Regulation (EC) No 1257/1999). This practice

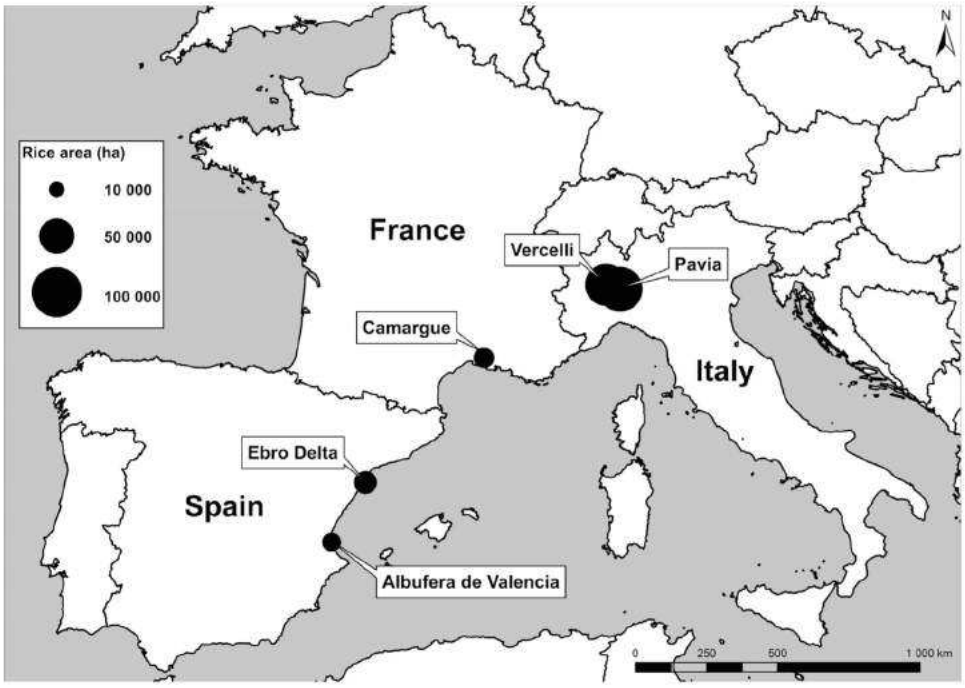

Fig. 1. Map of the five study regions in western Europe (the size of dots represents the area cultivated in rice, expressed in ha).

was historically used mainly for hunting purposes in Spain (Ferrer, 1986), but this modern legislation increased the area of flooded ricefields and the time during which they are flooded. This measure was implemented by the European Union in 1998 to promote environment-friendly methods of agricultural production, and applied to these two Ramsar-designated wetlands. The AES "ricefield winter-flooding" in both sites were applied as described until 2010 for Ebro Delta and 2012 for Albufera de Valencia but has been modified recently for reasons described in the Discussion.

Here we consider as "natural and semi-natural wetlands" all areas flooded by fresh or brackish water (temporary marshes, lagoons, ponds, hunted marshes), excluding salt pans (salines) and ricefields. In the Camargue, large remnants of the ancient natural wetland habitats can still be found, while in northwest Italy very little of the inland freshwater remains. However, in the Camargue, rice expanded mostly at the expense of freshwater and brackish marshes, and a total of 40,000 ha of natural habitats (33,000 ha wetlands) disappeared between 1942 and 1984 (Tamisier and Grillas, 1994). In the Ebro Delta, the progression of rice-farming has drastically changed overall habitat composition: at the beginning of the 20th century natural habitats still covered 28,000 ha (88% of the delta), then declined to 8000 ha (25%) today (Mañosa i Rifé, 1997). In Albufera de Valencia, the conversion of wetlands to anthropized habitats (including ricefields) began in the 16th century and lasted until the 1940s (B. Dies personal communication). Very limited information is available concerning wetland transformation in the Italian study regions as regards wetland transformation (Perennou et al., 2012). More generally, in northern Italy ca. 60% of the wetlands were reclaimed for agriculture between 1938 and 1984 (Nivet and Frazier, 2004).

2.2. Databases

2.2.1. Duck numbers

Our study focused on the six most common European dabbling ducks, i.e. gadwall (*Anas stepera*), northern pintail (*A. acuta*, hereafter pintail), mallard (*A. platyrhynchos*), common teal (*A. crecca*, hereafter teal), Eurasian wigeon (*A. penelope*, hereafter wigeon) and northern shoveler (*A. clypeata*, hereafter shoveler). These species are known to use ricefields during winter whenever these are available within their range (Mateo et al., 2000; Elphick et al., 2010a).

The Ebro Delta is the second largest wintering ground for waterfowl in Spain, followed by Albufera de Valencia (Oltra et al., 2001; Martí and del Moral, 2003). The Camargue is the most important wintering area in France for 5 of the 6 studied dabbling duck species (i.e., all but shoveler, for which it is the second most important site at the national scale, Deceuninck et al., 2014). These three regions all exceed the criterion of international importance for several duck species (>1% of bird population size, Wetlands International, 2014). In northwest Italy, 15,000 ha of Vercelli ricefields are recognized as Important Bird Areas (IBAs, Heath and Evans, 2000); in the Pavia province, 30,941 ha are designated as SPA – Special Protection Areas (IT2080501, Risaie della Lomellina).

The duck data used in the analyses mainly came from the International Waterbird Censuses (IWC) carried out every year in mid-January throughout Europe and coordinated by Wetlands International (Wetlands International, 2012). For the Camargue we used the mid-January aerial duck surveys (method explained in Tamisier and Dehorter, 1999), which were more consistent in covering the same area from year to year than the IWC, which combine systematic aerial and non-systematic terrestrial data. National and local Wetlands International coordinators provided the duck data from their respective regions for the present analyses. It is important to note that counts were carried out in all regions whilst ducks gathered at their day-roosts, which generally were not ricefields. However, despite this, some ricefields were still included in the counts in some regions (14,000 ha in the Albufera, Oltra et al., 2001; 22,723.9 ha in the Ebro Delta, Curcó and Bigas, 2012). Beside total duck abundance, expressed as the number of birds, we also compared species diversity between regions so as to determine if regions with more diverse habitats would also host a more diverse duck community. This was assessed through the Shannon-Weiner index which is based both on the number of

species and their average relative abundance over the 2002–2012 period.

2.2.2. Habitat data

The surface areas of wetlands other than ricefields, of the total ricefields of the previous summer and of winter-flooded paddies were obtained or computed for each winter of the 2002–2012 period directly for each of the five study regions.

To extract the natural or semi-natural wetland area of Pavia (Lombardy) and Vercelli (Piedmont) provinces, two land cover maps were used, one for Lombardy (DUSAF2008, database cartografia.regione.lombardia.it/geoportale) and one for the Piedmont region (LCP2008, Land Cover Piemonte, Classificazione uso del suolo 2008). Both were produced from digital color orthophoto maps (2005–2007 for Lombardy and 2000–2005 and 2007 for Piedmont, respectively). Corine Land Cover codes corresponding to wetland habitats were selected and a calculation of their total area was done with ArcGis software. Natural and semi-natural wetlands are considered to have been stable in these regions over recent decades (G. Bogliani personal communication), therefore the value of the surface area obtained for these wetlands in each of these regions with the above method was applied to all years of the 2002–2012 period.

In the Camargue, natural and semi-natural wetland area was available for the years 2001, 2006 and 2010 (Observatoire des Zones Humides Méditerranéennes, 2014). From these data, missing annual values were extrapolated using linear regression, which was assumed appropriate because of the gradual change of the Camargue wetland habitats over the last decades (Parc Naturel Régional de Camargue, 2013, annual rate of decline for period 1991–2001: 0.08%, Tour du Valat, 2009).

There is only one main wetland in Albufera de Valencia, a central lagoon covering 2,837 ha, with no change in area over the last 30 years (B. Dies personal communication). Owing to pollution from surrounding areas, this lagoon is hypertrophic and therefore provides little food for ducks (del Barrio et al., 2012). In the Ebro Delta, the decennial natural and semi-natural wetland area from Curcó (2004) was used as a reference for 1990, the value extracted by Observatoire des Zones Humides Méditerranéennes (2014) for 2005, and that given by Curcó and Bigas (2012) for year 2011. Missing annual values were computed from a linear regression between those dates, following the same procedure as in the Camargue.

The annual area of cultivated rice was extracted from databases of the national agriculture services: the Ente Nazionale Risi in Italy (http://www.enterisi.it), France AgriMer in France (http://www.franceagrimer.fr), and Ministerio de Agricultura, Alimentación y Medio Ambiente in Spain (http://www.magrama.gob.es).

A two step multi-temporal remote sensing approach with Landsat imageries (TM, ETM and OLI) was used to obtain the mean area of winter-flooded ricefields at each study site. Note that owing to the use of remote sensing, it was not possible to distinguish fields intentionally flooded by man from fields flooded by heavy rainfall. First, for each period of the annual rice cultivation cycle, at least 3 Landsat multispectral images were used to delineate and map the ricefields. These 3 Landsat acquisition dates corresponded to the main phases of crop production: (a) one image when the fields were devoid of any vegetation during winter (October to March), (b) one image when the fields were flooded after setting the young seedlings (end of spring and beginning of summer), and (c) one image when rice plants were mature, before harvest (July to September) (Fig. 2a, b, c and resulting map d).

This multi-temporal approach enabled us firstly to avoid confusion between ricefields and other aquatic habitats (e.g. marshes, lagoons, sea, etc.), and secondly to separate rice from other crops. We used two functions of the Spatial Analyst Tool of Arcgis. The function Reclass/Reclassify was used for identifying the ricefields that were flooded in winter for each image. Once rice crops were mapped for a given site and a given year, function Math Algebra/Raster Calculator was used to calculate the total flooded area for all the used images.

From this, the MNDWI (Modified Normalized Difference Water Index) was used to map open water areas (Hanqiu, 2006). The MNDWI enhanced open water features by efficiently suppressing built-up land noise as well as vegetation and soil noise (Fig. 2e and f). The calculation of this index is based on the Green band (G) and the ShortWave InfraRed band (SWIR) of Landsat:

$$\mathrm{MNDWI} = 1 - (\mathrm{SWIR}/\mathrm{G})/1 + (\mathrm{SWIR}/\mathrm{G})$$

The resulting water area map was then overlaid with the ricefield map produced during the previous step, and the GIS intersection between the two shapefiles was calculated (Fig. 2g and h). This figure represented the flooded area within all ricefields at a given site for a given date. The proportion of winter flooded ricefields was computed for each site each November, December and January whenever satellite images were available. The mean of these values (one to three, depending on available satellite images) was then used in the analyses. In practice, an area of flooded ricefields was available for 2 years of the 2002–2012 period in Albufera de Valencia (2002, 2003), 3 years in the Camargue (2002, 2003, 2006), Vercelli (2002, 2003, 2012), and Pavia (2002, 2003, 2012), and 5 years in the Ebro Delta (2002, 2003, 2007, 2010, 2011). Due to the limited number of satellite images available in Albufera de Valencia, missing annual data were complemented by information on winter flooded ricefields provided by the Dirección General de Innovación Agraria de la Consejería de Agricultura, Pesca y Alimentación of the Valencian community (http://www.agricultura.gva.es/) for the winters from 2003 to 2011 (except winter 2007) based on the CAP farmers declaration. The Albufera was the only region where we had access to such information. Because flooding policy has remained stable in each of the five regions during the last decade, we computed the mean proportional area of ricefields that was flooded over all available annual data in each region, and applied this mean number to all years of our study period (2002–2012).

2.3. Statistical analyses

2.3.1. Habitat features and duck abundance

All statistical tests described in this section were performed using R version 2.15.3 (R Core Team 2013).

The mean landscape features and the annual total duck numbers were firstly compared between the five study regions using an ANOVA with repeated measures on log-transformed proportions of wetlands/rice in the total area and log-transformed duck numbers, respectively, to meet normality criteria.

The potential relationship between duck abundance and habitat features was then analyzed using Generalized Linear Mixed-effects Models (GLMMs) with a negative binomial distribution (data overdispersed: package glmmADMB, function glmmadmb). In the GLMMs, dry rice, natural and semi-natural wetlands, flooded rice as well as total wetland (i.e. natural & semi-natural wetlands + flooded ricefields) and total rice (i.e. dry ricefields + flooded ricefields) areas were used as continuous predictor variables, while Site (5 modalities for the 5 study regions) and Year (to account for variation between years) were included as random factors. We tested the effect of total wetland area and its components (i.e. natural wetland area + flooded ricefield area) in separate models, to assess if duck abundance depended on wetland availability in general (i.e. total wetland area), or was more dependent on the availability of some wetland types (i.e. natural or artificial). We

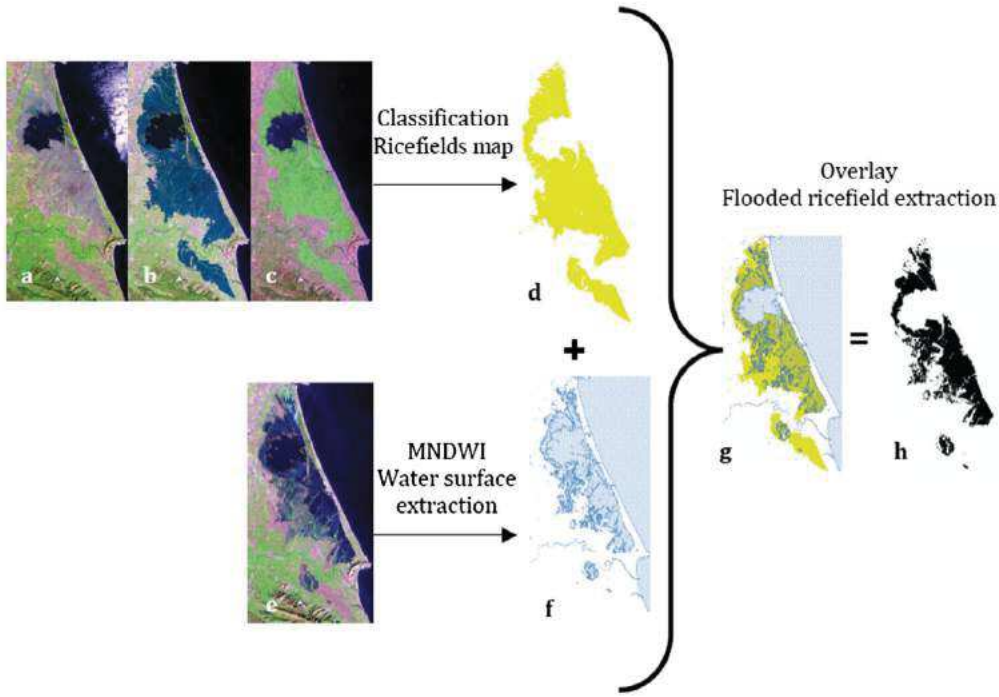

Fig. 2. Ricefield mapping derived from a multi-temporal Landsat analysis for year 2003: (a) Non-vegetated fields (10 March 2003), (b) Artificially flooded fields for rice cultivation (22 May 2003), (c) Mature fields before harvest (9 August 2003), (d) Ricefield delineation map derived from the 3 acquisition dates using an automatic remote sensing classification, (e) and (f) Extraction of water surface areas using the MNDWI (29 December 2002), (g) and (h) Extraction of the flooded ricefields for one acquisition date during the winter season (here, December) of the 2003 time period. The mapping technique is illustrated here with images of Albufera de Valencia.

repeated the same method for the ricefield areas (i.e. dry ricefields + flooded ricefields), called total rice area.

All predictors were z-transformed (in order to have means equal to 0 and standard deviations equal to 1) prior to the analyses. The Akaike's Information Criterion (AIC) was used to compare the set of possible models and to rank them (Burnham and Anderson, 2002). After ranking models according to their respective AIC, the principle of parsimony was used to find the best trade off between biases related with the use of a simple model versus the loss of performance of a more general model.

The best model is the only one to be presented in details in the results section.

2.3.2. Effect of flooding regime on the number of ducks

To test whether regional duck population trends were related to the AES "winter-flooding" application, we compared the trends in the numbers of ducks at the Ebro Delta and Albufera de Valencia before and after winter flooding was introduced. The spatial images were insufficient to compare the proportion of rice actually flooded before and after the implementation of the measure. Hence, two periods of similar duration (with the date of AES application chosen as the change point) were considered at each site: 1989–1999 (Ebro) and 1989–2001 (Albufera) were the periods before the AES, and 1999–2010 (Ebro) and 2001–2010 (Albufera) were the post-AES implementation periods. The most recent data (i.e. 2011–2012) were removed from the analysis as flooding politics changed again in the Ebro Delta after winter 2010, with parts of the ricefields currently kept dry as a measure against the spread of the exotic apple snail *Pomacea insularum* (Curcó and Bigas, 2014). Duck population trends were calculated using TRIM, a freeware widely used in Europe to implement Poisson regressions to analyze time-series of counts, especially for waterbirds (Pannekoek and van Strien, 2001). The time effects model with imputed indices was used, considering serial correlation and overdispersion (e.g. Wretenberg et al., 2007) to estimate the overall trends and their 95% confidence intervals over the whole study period (1989–2010) for each of the two regions. This procedure was then used with years 1999 (Ebro) and 2001 (Albufera) as change points in linear trend models. Finally, to test if any increase in duck numbers was explained by a global trend at the flyway scale, the analysis was performed for the Camargue, which was considered a control site, using 2000 (the mid-point between AES implementation at Ebro and Albufera) as the change point, i.e. pre-AES years: 1989–2000, post-AES years: 2000–2010.

3. Results

3.1. Habitat features and duck abundance

Mean wetland percentage cover differed greatly among the five regions (ANOVA: $F_{4,49} = 12{,}648$, $P < 0.001$), with the proportion of natural and semi-natural wetlands versus ricefields highest in the Camargue, intermediate in the Ebro Delta, and lowest in the Albufera and Italy (Fig. 3). The two Italian provinces were almost completely covered with ricefields (only 3% of natural and semi-natual wetlands in Vercelli). The mean proportion of ricefields that were flooded during winter was 62% on average in the Ebro Delta and Albufera de Valencia. The figure was 9% on average in Camargue. The other extremes were the two Po Valley provinces in Italy with only 0.17% (Vercelli) and 0.28% (Pavia) of the ricefields being flooded during winter.

Major differences in mean total duck numbers were also observed between the five study regions (ANOVA: $F_{4,\ 49} = 209$, $P < 0.001$): the Camargue and the Ebro Delta had the greatest numbers while the two Italian provinces, despite being the largest rice farming areas in Europe, had very few ducks (Table 1). The Albufera de Valencia and the Italian study regions have similar natural and

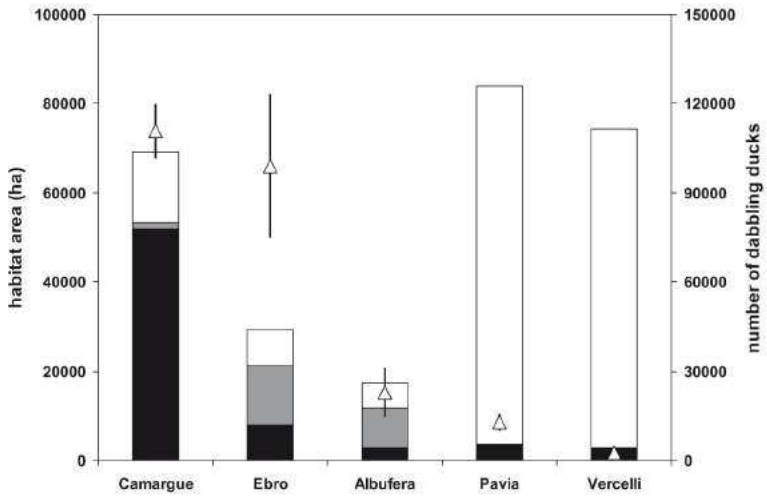

Fig. 3. Mean wetland habitat composition and abundance of wintering dabbling ducks (triangles, from January censuses) in five major European rice production regions (black: natural and semi-natural wetlands, grey: flooded ricefields, white: dry ricefields). Average values over the 2002–2012 period, vertical bars for the numbers of ducks indicate standard error.

Table 1
Abundance of six dabbling duck species ± SE in five major European rice production regions, and mean relative percentage of each species in the duck community of each region (±SE, in parentheses). Average values over the 2002–2012 period, January censuses.

Region	Duck species					
	A. platyrhynchos	*A. crecca*	*A. acuta*	*A. strepera*	*A. penelope*	*A. clypeata*
Camargue	43,130 ± 3039 (40 ± 2)	32,670 ± 4386 (29 ± 3)	931 ± 471 (1 ± 0.2)	15,860 ± 7168 (14 ± 1)	9790 ± 1140 (9 ± 1)	8290 ± 847 (8 ± 1)
Ebro	53,202 ± 3951 (55 ± 3)	21,417 ± 2837 (21 ± 2)	2867 ± 701 (3 ± 0.4)	3540 ± 387 (3 ± 0.3)	3055 ± 590 (3 ± 1)	14,968 ± 2,272 (15 ± 2)
Albufera	15,820 ± 1548 (71 ± 3)	1591 ± 382 (7 ± 1)	504 ± 114 (2 ± 0.4)	100 ± 17 (0.4 ± 0.04)	209 ± 77 (1 ± 0.4)	4498 ± 898 (19 ± 3)
Pavia	11,651 ± 824 (90 ± 1)	1122 ± 123 (9 ± 1)	6 ± 3 (0.05 ± 0.02)	37 ± 11 (0.3 ± 0.1)	58 ± 27 (0.4 ± 0.2)	16 ± 5 (0.1 ± 0.1)
Vercelli	2379 ± 493 (92 ± 2)	145 ± 34 (7 ± 2)	1 ± 0.5 (0.05 ± 0.03)	4 ± 4 (0.2 ± 0.2)	2 ± 1 (0.2 ± 0.1)	12 ± 4 (0.6 ± 0.2)

Table 2
Set of all candidate GLMMs testing the relationship between the environmental variables (NatWet: natural & semi-natural wetlands, FloodRice: flooded rice, DryRice: dry rice and TotWet: natural & semi-natural wetland + flooded rice, TotRice: dry rice + flooded rice) and the mean annual numbers of dabbling ducks in five major European rice production regions over the 2002–2012 period.

		AIC	ΔAIC
Ducks	NatWet***+FloodRice***	1177.97	0
	NatWet**+FloodRice*+DryRice	1179.87	1.90
	TotWet*+DryRice	1180.66	2.69
	TotWet**	1180.90	2.93
	NatWet + DryRice*	1181.77	3.80
	DryRice*	1181.83	3.86
	TotRice*	1182.21	4.24
	FloodRice + DryRice	1182.51	4.54
	NatWet + TotRice	1182.55	4.58
	NatWet	1183.07	5.10
	FloodRice	1183.08	5.11

Significance of the predictor variables is represented by:
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

semi-natural wetland areas, but the Albufera had both more flooded ricefields and more ducks (Fig. 3, Table 1).

Two models (ΔAIC scores <2) explained differences in mean duck numbers better than the other models (Table 2). The first model was considered as the best one as it was the simplest. This model contained site-specific areas of the two wetland habitat types (ducks~ flooded rice + natural & semi-natural wetlands). The mean number of ducks at a site was positively related with the area of flooded rice (Table 3, Fig. 4) and with the area of natural & semi-natural wetlands.

Table 3
Model-averaged parameter estimates, standard-errors, z values and P values of the predictor variables of the best GLMM (i.e. lowest AIC) testing the relationship between environmental variables (areas of natural & semi-natural wetlands, winter flooded ricefields) and the mean annual numbers of dabbling ducks in five major European rice production regions over the 2002–2012 period.

Fixed effects	Estimate	s.e	z value	Pr(>|z|)
(Intercept)	10.06	0.26	39.52	<2e−16***
Flooded rice	1.01	0.25	4.01	6.0e−05***
Natural & semi-natural wetlands	1.07	0.25	4.23	2.3e−05***

*** $P < 0.001$.

The Italian sites had scarce natural and semi-natural wetlands, and simultaneously mostly hosted granivorous ducks (mallard, teal and pintail). Herbivores (gadwall, wigeon) were more abundant in Camargue, and to a lesser extent in the Ebro Delta. Shovelers, which usually have more zooplankton in their diet, were more abundant in the Ebro Delta (Table 1). The Shannon-Weiner diversity indices (H) were greater for the Camargue (1.45) and the Ebro Delta (1.28), intermediate at Albufera de Valencia (0.91), while values as low as 0.36 (Pavia) and 0.27 (Vercelli) were recorded in the two Italian regions.

3.2. Effect of winter ricefield flooding on the number of ducks

Over the 1989–2010 period, the numbers of wintering dabbling ducks in the Ebro Delta, Albufera de Valencia and the Camargue all increased significantly, at approximately similar rates, although profound changes occurred in the Spanish regions over the period

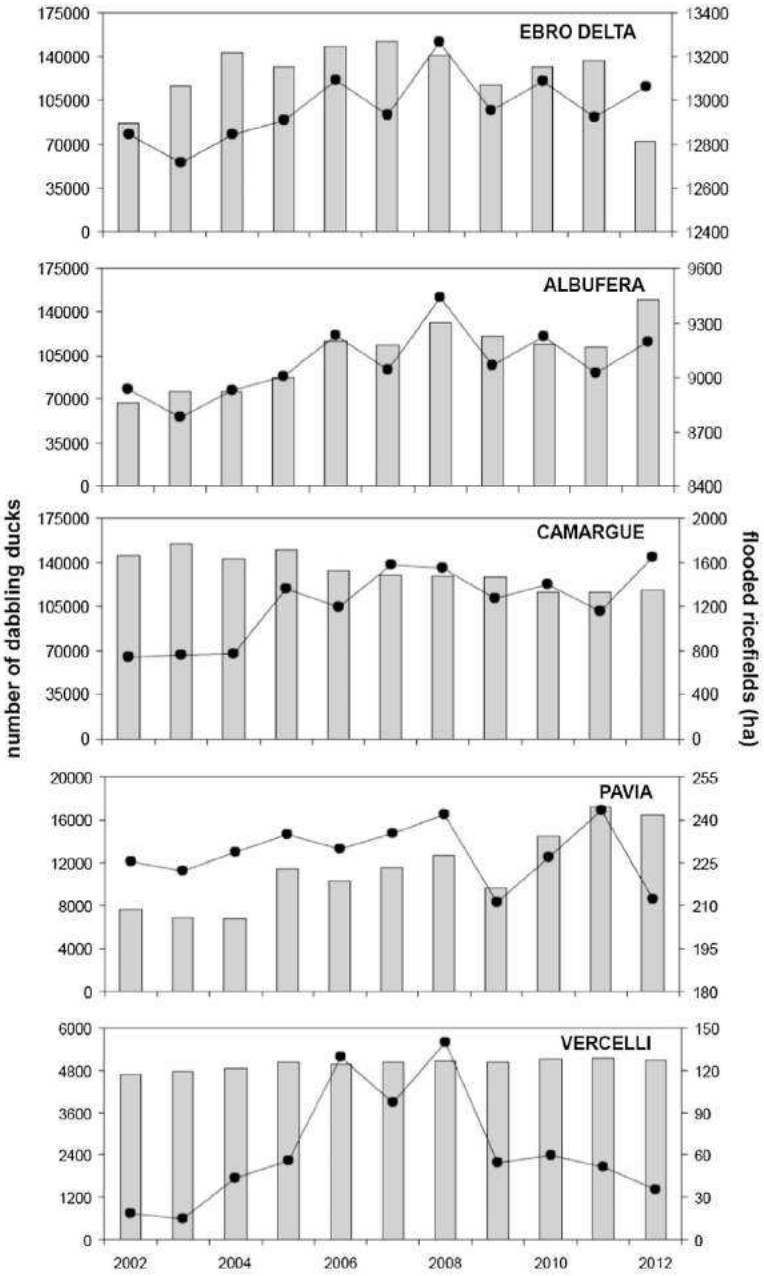

Fig. 4. Annual abundance of six dabbling ducks species (black dots) (January census) and mean area of winter-flooded ricefields (left) in five major European rice production regions (grey bars) over the 2002–2012 period. Note that scales differ between regions.

Table 4
Annual population rate of change (in percentage) with 95% confidence intervals (CI) and trend interpretation for six dabbling ducks over two time periods (Pre and Post winter flooding AES) in three rice production regions of southwestern Europe. The Camargue was considered to be a control region. Trend analysis performed with TRIM. All nine trends were significant $P < 0.01$.

Region	Pre winter flooding AES	Post winter flooding AES	Full period 1989–2010
Ebro Delta	−0.91 (−0.83 to −0.99) Moderate decline	+6.03 (5.97 to 6.09) Strong increase	+3.44 (3.42 to 3.46) Moderate increase
Albufera de Valencia	−5.33 (−5.27 to −5.37) Steep decline	+12.47 (12.29 to 12.65) Strong increase	+1.10 (1.06 to 1.14) Moderate increase
Camargue	+0.72 (0.70 to 0.78) Moderate increase	+8.48 (8.56 to 8.64) Strong increase	+3.05 (3.03 to 3.07) Moderate increase

considered (Table 4, Fig. 5). However, while such a positive trend was already apparent before the years 2000 in the Camargue, the numbers of wintering ducks in the two Spanish regions were declining. Only after the implementation of AES did the Spanish trends increase, especially so at Albufera, then becoming positive as in the Camargue (Table 4, Fig. 5).

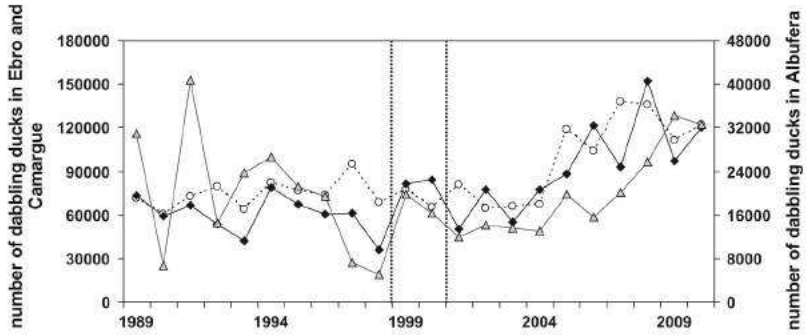

Fig. 5. Annual numbers of wintering dabbling ducks in the Camargue (open circles), the Ebro Delta (black diamonds) and Albufera de Valencia (grey triangles) over the 1989–2010 period. The two dotted lines indicate the years of the ricefield winter flooding AES implementation in the Ebro Delta (1999) and the Albufera (2001).

4. Discussion

This study demonstrates the benefits that can be expected from flooding fields post harvest in European rice growing regions: wintering ducks were generally more abundant where flooded ricefields were widespread, and site-specific trends in duck numbers became more positive after implementation of winter flooding as an AES.

Most of the world's rice is grown under flooded conditions (86%, Chang and Luh, 1991), but the practice of flooding the fields after harvest is more variable, and mostly promoted for environmental conservation, hunting purposes, or straw disposal (e.g. in North America, Eadie et al., 2008; in Japan, Kurechi, 2007; Tajiri and Ohkawara, 2013; worldwide, Elphick et al., 2010b). The present comparative study stemmed from the observation that most studies on the importance of this practice at the regional scale were from Japan or North American regions. Conversely, although knowing that the extent to which European ricefields get flooded in winter is largely dependent on national agricultural policies (through rice AES), the way this is practiced at the flyway scale in Europe and the consequences for duck numbers remained unexplored. This led us to expect clear differences in terms of landscapes between countries and regions, and possible translation into contrasting numbers of wintering ducks.

The number of wintering ducks was positively related to the area of natural and semi-natural wetlands. This can be explained biologically since ducks search for such habitats as their diurnal roosting sites (e.g. large ponds and lakes) and also rely on these as nocturnal foraging grounds to some extent (e.g. shallow vegetated wetlands, see for example Tamisier and Dehorter, 1999 for the Camargue). In this context, it is interesting to note that Elphick (2008) recorded a positive effect of flooded ricefield area onto duck density in California, but no such effect for natural wetland area. In California ducks use ricefields both as day-roosts and foraging areas, which can explain the preponderant effect of these habitats. Conversely, European ducks mostly roost in natural wetlands and chiefly use flooded ricefields as nocturnal foraging grounds (Tamisier and Dehorter, 1999). It thus makes sense that in this continent the area of both habitat types jointly affects duck abundance. Also in accordance with this, duck abundance was negatively correlated to the area of dry rice (negative effect size of the dry rice variable when considered in the models, results not shown). Dry ricefields do constitute a valuable habitat to some birds such as e.g. raptors and granivorous passerines (Elphick, 2004). For species like ducks, however, the lack of water prevents any efficient use of the potential food resources (e.g. Guillemain et al., 1999), and ducks do not rest on completely dry land during the day either, so the development of rice areas without flooding represents a lost opportunity. Converting a natural wetland into a dry ricefield can hence also be considered as habitat loss for ducks.

Conversely, the number of wintering ducks increased with the area of flooded ricefields. Harvested ricefields have abundant waste grains, weed seeds and invertebrates (Stafford et al., 2010), which are made accessible to ducks by the addition or the retention of water in the fields after the rice crop season, hence likely explaining the above relationship. Earlier studies in Japan and the US have demonstrated increases in local duck numbers with increased local winter rice flooded areas (e.g. Day and Colwell, 1998; Shimada et al., 2000; Tajiri and Ohkawara, 2013), or recorded larger numbers of non-breeding ducks in flooded than unflooded fields of the same area (Elphick and Oring, 1998, 2003). Studies at a broader geographic scale are however far less numerous: in Europe only Toral and Figuerola (2010) demonstrated a positive relationship between European waterbird population trends and an index of rice field use during the autumn in Spain, highlighting how the provision of ricefields at key migration sites can enhance whole populations. To our knowledge, the present study is the first to consider how the post-harvest management of such fields, through their flooding, can promote duck numbers among scattered winter quarters within the ducks non-breeding range in Europe.

Flooded fields improve the attractiveness of winter quarters by increasing global wetland area, sometimes compensating to some extent for the lack of such natural wetlands (cf. the two Italian provinces). Wetlands in the broad sense, i.e. either natural or artificial (flooded ricefields) hence seemed to jointly promote large numbers of wintering ducks. However, the best model in our analysis was not among those comprising the variable "total wetlands" (i.e. sum of natural & semi-natural wetland + flooded rice areas), but rather had each variable (natural & semi-natural wetland area and flooded rice area) considered separately (Table 2). Thus, a certain area of flooded ricefields was not strictly equivalent to the same area of natural wetland. Both present almost equivalent effect size, indicating that they are both important and complementary. Indeed, it is possible that these two habitat types do not play the same role: in Camargue, for instance, natural wetlands typically provide nocturnal foraging areas and day roosts to wintering ducks (Tamisier and Dehorter, 1999), while flooded ricefields are mostly used as nocturnal feeding grounds (Pirot, 1981; Mesléard et al., 1995), but are probably too frequently disturbed by humans or predators to represent valuable day-roosts. Some earlier studies have found lower bird numbers, species richness and species evenness in rice fields than in neighbouring wetlands, but these were based on diurnal censuses (Tourenq et al., 2001a; Bellio et al., 2009; Taylor and Schultz, 2010; Guadagnin et al., 2012). Such surveys hence completely overlooked the use of rice fields by ducks foraging at night (McNeil et al., 1992). Actually, the present results suggest that the number of ducks at day-roosts (mostly large lakes or marshes, where they were censused during

IWC or aerial surveys) also depends on the availability of suitable nocturnal foraging grounds, which includes flooded ricefields.

Beyond total duck numbers, there was also a greater diversity of dabbling duck species where natural wetland area was greater and/or the local habitat matrix contained large shares of natural and artificial wetlands simultaneously (that is, Camargue > Ebro Delta > Albufera > Pavia > Vercelli). In Italy, where dry ricefields are the main habitat, the duck community was simple and mostly composed of granivorous species (mallard, teal and pintail). Conversely in the Camargue, which still has a diversity of wetland types, other species like herbivorous gadwall and wigeon were more numerous. Simultaneously conserving natural wetlands and improving adjacent agricultural wetlands by appropriate post-harvest management hence creates a heterogeneous landscape mosaic particularly attractive and beneficial to a varied waterfowl community (see also King et al., 2010). The comparison of Albufera de Valencia and the two provinces of Italy provides some insight about the extent to which flooding ricefields can provide a complement to natural wetlands: such natural and semi-natural wetlands are similarly few in all three studied areas, but ricefield flooding in the Spanish region led to much higher numbers of ducks and higher species diversity, likely because the Albufera lagoon already provided an ideal day roost and the flooding of fields made vast areas of nocturnal foraging grounds accessible to the birds.

In the Camargue, most ducks concentrating at large roosts during daylight hours disperse at dusk into a variety of shallow wetlands, 78% of which are private properties (Brochet et al., 2009). While the large day-roosts have long been identified and protected in one way or another, the provision of more nocturnal foraging grounds and the protection of some of these have now been identified as priorities for conservation (Brochet et al., 2009). The present study suggests that the simple flooding of harvested ricefields may be a valuable technique to provide such nocturnal habitats, likely translating into more abundant and varied wintering duck communities. If some flooded ricefields become completely free from human disturbance, these may even potentially turn into suitable day-roosts as observed in North America (Rave and Cordes, 1993).

We recognize that the relationship between duck numbers and area of flooded ricefields described above is based only on a correlative analysis. However, the changes in habitat management policy in the Ebro Delta and Albufera de Valencia, through the introduction of rice winter-flooding AES, also provided a test of this hypothetical relationship. The trends in duck numbers in these regions were negative before the 2000s, while ducks were increasing only a few hundred kilometers to the north in the same flyway, in the Camargue, reflecting the gradual increases in dabbling duck numbers generally observed throughout their flyway over the last decades (Wetlands International, 2014). Temporal autocorrelation analyses between these three times series (not shown) also suggest that AES implementation has now led the Spanish sites to follow the general European trend, whereas they were disconnected beforehand. The implementation of a new AES promoting overwinter flooding induced a complete change of the situation, with the Spanish regions then following a trend broadly similar to that of the Camargue, and consistent with the more general pattern at the flyway scale (Wetlands International, 2014). This result combined with the spatial analyses above jointly suggested that flooding existing ricefields is genuinely beneficial to wintering ducks, likely because this makes existing food resources within the rice stubble accessible to the birds.

Winter flooding of agricultural fields thus seems effective to provide European ducks with suitable habitat, but issues remain regarding preferential timing, depth, and duration of winter floods (see also Twedt and Nelms, 1999). Elphick and Oring (1998, 2003) observed that American dabbling duck numbers were greatest at winter flooding depths from 14 to 22 cm, and advised shallow average depths (10–20 cm), to guarantee access to available invertebrates and seed resources also to other waterbirds. Timing and duration of flooding should be adjusted among regions so as to match the birds' main autumn migration period (Elphick et al., 2010b). If fields are flooded too early, spilled grain and weed seeds may decompose or be depleted by other organisms before the arrival of migratory birds (Nelms and Twedt, 1996; Greer et al., 2009). When carefully practiced, flooding of ricefields may translate into greater local residence time of birds during winter, as observed in Spain (in the Ebro Delta, Ferrer, 1986 versus Oltra et al., 2001) or changes in the general distribution of wintering birds, as observed in California, USA (Fleskes et al., 2005). Lastly, artificially flooded ricefields may function as a buffer during critical drought periods (Fasola and Ruiz, 1996; Tourenq et al., 2001a; Kloskowski et al., 2009), thus providing a more predictable habitat to waterbirds than some temporary natural wetlands (Márquez-Ferrando et al., 2014).

Besides the expected benefits of winter flooding of ricefields in terms of bird habitat provisioning, this practice could also bring agronomic benefits to farmers. Unlike stubble from other crops, the silica content of rice straw confers unsuitable characteristics for several uses, and rice straw disposal is a problematic issue. Burning is a common practice, e.g. in the Camargue, but causes problems of air pollution (Monier et al., 2009). Flooding of rice stubbles was expanded to California after the implementation of the California Rice Straw Burning Act (AB 1378) of 1991, which imposed a strong reduction in burning. Flooding in itself helps rice straw decomposition, which is further promoted by the trampling of waterbirds using the fields (Bird et al., 2000; van Groenigen et al., 2003). The agronomic benefits of flooding ricefields have been studied at length in North America (Manley et al., 2005), and are also being revealed in Europe (e.g. in the Camargue, Brogi et al., unpublished data).

Given the likely benefits of flooding ricefields during winter in terms of both biodiversity and agronomy, it makes sense that this practice has been supported via AES in northern Spain. Up to now, winter flooding in France and Italy (Modena and Ferrara provinces in Emilia-Romagna region) is however only promoted at a small scale by local hunting groups within some private properties (Mathevet and Mesléard, 2002; R. Tinarelli, and A. Brangi, personal communications). In Italy, Agri-Environment Schemes in Emilia-Romagna, Lombardy and Piedmont may promote winter flooding in the coming years because this has been recommended as a conservation measure in Special Protected Areas (R. Tinarelli personal communication). There are however hurdles to the general introduction of winter flooding in European ricefields. This would for example be easier in Italy where fields are flooded by gravity than in France, where water has to be pumped from the Rhône river and energetic costs are currently too high to encourage flooding without financial compensation. Some opposition has arisen in Italy, which was in part due to the fact that some of the irrigation channels are dried for maintenance during the winter and, therefore, only a fraction of rice growers could benefit from the contribution. Invasive alien species in such artificially-created wetlands may also become an issue, and in the Ebro Delta many ricefields have actually been kept dry or flooded with sea water since 2010 as a measure against the spread of the exotic apple snail *Pomacea insularum* (Curcó and Bigas, 2014), although ducks can help to control this pest (Green and Elmberg, 2014). The proposed new rural development Act of the region (Pla de desenvolupament rural de Catalunya (PDR) (2014–2020) PDR 2014–2020, 2015) proposes drying harvested ricefields during winter in areas highly invaded by the Apple Snail and keeping flooding the non-affected fields.

In any case, economics are the main driving factor of these and other agricultural practices; in Spain, the financial crisis and

associated political decisions likely induced the end of the financial AES winter flooding help to rice farmers in Albufera de Valencia since 2012. The proposed new rural development Act of the region (Programa de Desarrollo Rural de la Comunitat Valenciana PDR CV 2014–2020, 2015), only considers to keep flooded the lowlands ricefield until mid-January. In France as well as in Spain, it is the rice industry in general that could be affected by economic changes, especially since the CAP 2015 plans some changes to the financial support to the cultivation of this crop. As a matter of fact, changes in the agricultural landscape have already been observed (reduction of ca. 25% of the rice in the Camargue in 2013 and replacement by dry crops such as wheat or vegetables, C.A. Pernollet, unpub. data). In the early 1980s, the rice area in France already declined to only 4000 because of reduced financial incentives (Mañosa i Rifé, 1997). The decoupling of the direct payments applied in the 2003 CAP have proven that they could have negative consequences on biodiversity but could be offset by strengthening AES (Brady et al., 2009).

4.1. Conservation and policy implications

The European Commission often lacks the factual data necessary to implement an AES, and scientific assessment of the efficiency of current schemes is also urgently needed (e.g. Tourenq et al., 2001b; Ernoul et al., 2013). This study shows that the flooding of rice stubble after harvest is effective in providing attractive habitat to dabbling ducks in Europe. It is easier to flood one hectare of ricefield than (re)create one hectare of natural wetland. There may be some technical hurdles to the implementation of this practice in some rice growing areas, but the environmental as well as agronomic benefits that can be expected suggest this should be promoted (and financially supported where necessary) throughout the wintering range of European waterfowl. Finally, passive flooding through rainwater retention is a low-cost procedure that could be employed in areas where flooding costs are too high (e.g. in Portugal, Lourenço and Piersma, 2009; in Japan, Shimada et al., 2000).

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Article 3:

Seed Availability and Waterfowl Use of Rice fields in Camargue (France): the Role of Post-harvest Practices

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ABSTRACT

European rice fields provide potential nocturnal foraging habitat to waterfowl during winter. Agricultural practices may influence seed availability and accessibility, thereby influencing the extent to which ducks use this managed habitat. To assess the potential influence of post-harvest stubble-management practices on waste rice and weed seed densities, and to evaluate the link of the latter with nocturnal duck abundance, a large-scale experiment was conducted in rice fields of the Camargue, France. Different post-harvest treatments (flooding, burning, chopping, disking, ploughing and their combinations) were tested. The quantity of available seeds was assessed three times across the winter season, from harvest in late October to departure of the wintering ducks in early February, over two winters (2012/13–2013/2014). Nocturnal duck use of these fields was monitored during the second year. Initial post-harvest rice and weed seed densities were positively correlated and highly variable (average: rice seeds: 350 kg/ha ± 58 SE; weed seeds: 142 kg/ha ± 21 SE). Mean seed availability was not dependent on straw management procedure (burning, chopping or disking). Average rice density decreased by 89% and weed seed density by 69 % between harvest and late winter. Seed depletion rate was highly dependent on initial seed density, and was greatest in plowed fields. Winter flooding did not significantly affect seed depletion rate, but was the main determinant of nocturnal duck use of the fields (flooded: 23.5 ducks/ha ± 2.3 SE, unflooded: 0.3 ± 0.1 SE). Duck numbers were lower in burned fields than in chopped or disked fields. One hectare of Camargue ricefield could support an average of 45 mallard-sized ducks per hectare per day for the entire wintering season (i.e. 5,373 duck-use days/ha, (DUDs/ha)) given initial post-harvest seed densities. Harvested rice fields have a great potential as nocturnal foraging habitat for wintering ducks in the Camargue. The present study suggests that plowing should be avoided and flooding promoted to better allow ducks to use of these fields.

KEY WORDS food resources, nocturnal surveys, post-harvest management, rice, waterfowl, winter flooding.

Around 12% of the Earth‘s land area is covered by farmlands (FAO, 2009). Certain populations of birds rely heavily on these agricultural habitats, and in turn can influence farming activities and crop output (e.g. Donald et al. 2001, Whelan et al. 2008). Food availability and dietary requirements have been quantified for some avifauna inhabiting European agricultural landscapes, but research has focused primarily on dry crops and passerines (Holland et al. 2006, Eraud et al. 2015). However, rice fields are typically semi-aquatic environments, and have been recognized as a globally important foraging habitat for waterbirds (Elphick et al. 2010a). The extent to which these artificial agricultural wetland habitats are used by wintering waterfowl in Europe has not been deeply described (Longoni 2010). In addition, foraging habits are likely more difficult to determine in European rice-growing regions because waterfowl hunting and other disturbances result in most foraging activity to occur at night (McNeil et al. 1992, Tamisier and Dehorter 1999). Furthermore, the variability of post-harvest management practices, such as the extent to which ricefield are flooded during winter, may cause food accessibility and field use to greatly fluctuate at the flyway scale, complicating estimates regarding the importance of ricefield management practices to migratory waterbirds (Pernollet et al. 2015). This knowledge is critical given that rice fields represent one third of the suitable waterbird habitats in southern Europe (Toral and Figuerola, 2010), and that their use of these habitats in winter has likely been greatly underestimated (Tourenq et al. 2001a).

North American researchers have reported high quantities of incidental waste rice following harvest (Eadie et al. 2008, Stafford et al. 2010), a food supply readily exploited by numerous species of waterfowl. Additionally, the seeds of weeds found in rice fields are also known to be consumed by waterfowl (Stafford et al. 2010). The extent to which post-harvest farming practices influence rice and more particularly weed seed availability has received very limited attention (except for Manley et al. 2004, and Marty et al. 2015), and very few studies have tried to link food availability to the use of fields by waterfowl, an important step in understanding their role in depletion of the seed bank (waste rice and weed seeds; see Havens et al. 2009, Geer et al. 2009). As a result, the extent to which straw management (burning, chopping), mechanical treatment (disking, plowing), type of farming (organic, conventional), crop rotation (number of years under rice cultivation) and winter flooding influence the seed bank and the relationship between seed abundance and field use by ducks remains unclear (Elphick et al., 2010b).

Food availability studies (Pirot et al. 1982, Tamisier and Dehorter 1999) and nocturnal duck surveys (Pirot et al. 1982, Mesléard et al. 1995) in flooded rice fields and natural wetlands have been conducted in southern France in the past. The present study is however the first to focus on rice fields and consider all post-harvest management techniques practiced in the area. Such a study is particularly relevant given that recent changes in duck migration phenology seem to be attributed to local habitat changes (Guillemain et al. 2015); that rice and associated weed seeds comprise a huge portion of the diet of ducks wintering in the Camargue (Brochet et al. 2012); and because the provision and protection of nocturnal foraging grounds are paramount to the conservation of waterfowl in the Camargue (Brochet et al. 2009), the most important winter quarter for waterfowl in France and one of the most important in Europe (Deceuninck et al. 2014, Critical Site Network Tool 2015).

In undertaking this study, our objectives were to (1) quantify and characterize the seed bank available to waterfowl at the onset of winter, expecting similar seed densities to those described in North America, where farming practices are equivalent, (2) test the effects of farming practices on initial seed mass and on seed depletion through the winter, expecting

greater seed availability in unburnt fields, especially when only a light superficial treatment of the soil is practiced, as opposed to plowing, and (3) determine which variables best explain nocturnal duck abundance, expecting a major influence of winter flooding. We then provide an updated estimate of carrying capacity for foraging waterfowl on post-harvest Camargue rice fields (duck-use days/ha, (hereafter DUDs), Reinecke et al. 1989), and discuss how the promotion of specific post-harvest practices could potentially improve carrying capacity.

STUDY AREA

This study was conducted on the Rhône River delta known as the Camargue, southern France (43°30'N, 04°30'E). Virtually all rice grown in France comes from this area. The Camargue climate is typically Mediterranean, with hot, dry summers, mild winters, and rainfall concentrated during fall and spring. This, combined with saline soils, restricts agricultural crops to either rice monoculture (sometimes more than 50 successive years of rice cultivation in the same field) or rice–wheat–alfalfa rotation (on average 3–5 consecutive years for each crop) (Barbier and Mouret 1992). 60,000 ha of the delta's 145,000 ha are wetlands, of which ca. 15,000 ha are rice fields (details in Tamisier and Dehorter 1999). On average, approximately 6 % of the area is cultivated under organic farming, with two years of organic rice cultivation generally being possible before weed encroachment significantly reduces yield (INRA 2012). The Camargue is one of the most important winter quarters for dabbling ducks at the European flyway scale (Critical Site Network Tool 2015). Migratory waterfowl begin arriving from September-October and numbers are at a maximum in January (Tamisier and Dehorter 1999).

Camargue rice fields are typically flooded between seeding and harvest (April to September), and kept dry in stubble until being plowed or disked for straw incorporation, usually early in winter. Disposal of rice straw is a challenge because of its high silica content which makes it resistant to decomposition (Monier et al. 2009). Currently, approximately 75 % of residual rice straw is burned, the remainder chopped (Monier et al. 2009). While burning straw is currently tolerated, concerns surrounding air pollution might soon bring about policy changes that limit or eliminate the practice entirely (Couderc 2013). About 9% of the Camargue rice area is flooded post-harvest for waterfowl hunting purposes (Pernollet et al. 2015), with most hunting occurring on private estates from late August to late January (Mathevet and Mesléard 2002).

METHODS

Seed sampling design

Core samples were collected from 52 post-harvest rice fields on farms scattered across the delta. 16 fields on 5 farms were sampled during the 2012–2013 winter season, and 36 fields on 8 farms during the 2013–2014 winter season (two farms were sampled both years). Fields were selected to represent the main post-harvest practices employed by rice farmers in the Camargue and to provide a broad geographic coverage of the area (Fig. 1, Table 1). The average area of these fields was 3.27 ha ± 0.26 SE (range: 1.12–8.49 ha). 1 to 8 fields were selected per farm, and fields of the same farm were generally adjacent to each other. Sampling occurred in a randomized block design on fields managed conventionally or organically, with or without flooding, and treated post-harvest by either burning, chopping, disking, or plowing the field (Table 1).

While organic rice production represents only 6% of total Camargue rice area (INRA 2012), in our study design the percentage was increased to 14% (7 of 52 fields) to improve statistical power of the comparisons. Flooded fields here were those where farmers intentionally pumped water in; "dry" fields included those where water gates were left open but which nonetheless may have been temporarily flooded during heavy rainfall events.

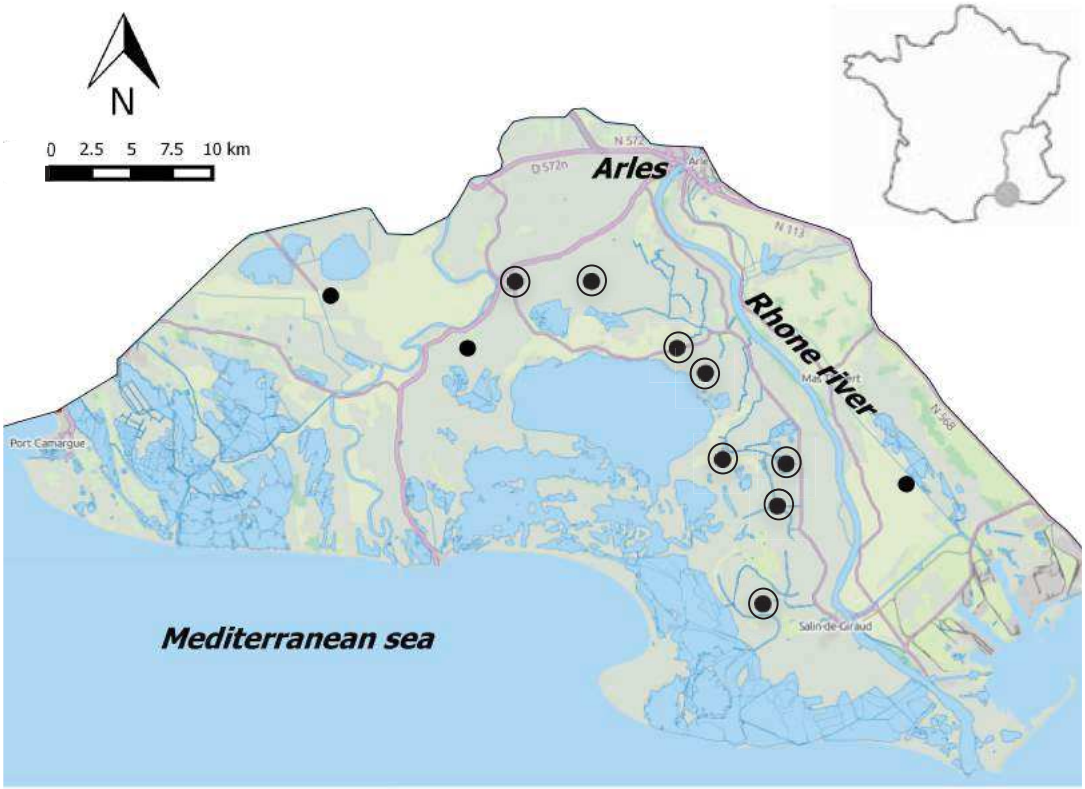

Figure 1. Map of the Camargue showing the 11 rice farms where soil samples were collected during winter seasons 2012–13 and 2013–2014 (points). Eight of these were also visited during winter 2013–2014 for nocturnal waterfowl surveys (open circles) (a black and white version is available).

Table 1. Agricultural treatments across the winter in 52 Camargue rice fields studied during winters 2012–2013 (n = 16) and 2013–2014 (n = 36). The three straw management procedures relate to the three periods: 1) early winter (late-Oct/early Nov), 2) mid-winter (mid-Dec), and 3) late winter (early-Feb). Flooding of the fields is indicated, together with type of farming (C: Conventional, O: Organic).

Straw Management	Burned Burned Burned		Burned Burned Disked	Burned Disked Disked	Burned Plowed Plowed		Chopped Chopped Chopped			Chopped Chopped Disked		Chopped Chopped Plowed	Chopped/Disked Chopped/Disked Disked	
Winter Flooding	No		Yes	No	Yes	No	Yes	No		Yes	No	Yes	No	Yes
Type of Farming	C	O	C	C	C	C	C	C	O	C	C	C	C	C
Number of Farms	2	2	2	1	1	2	1	3	2	2	2	2	4	1
Number of Fields	3	3	5	2	1	4	3	4	4	9	4	2	5	3

We collected soil samples from all fields three times per year over the two wintering seasons – for our purposes, "wintering season" is the period during which migratory waterfowl are present on their southern (i.e. winter) territory, and designations of early, mid, and late winter do not coincide with the winter season in the traditional sense. The first round of sampling occurred in late October/early November (early winter) immediately following harvest, the second in mid-December (mid-winter), and the third in early February (late winter). Seeds were collected in a uniform grid across the field of 9 standard cylindrical core samples, with a corer 10 cm in diameter and 5 cm deep (392.5 cm^3, 78.5 cm^2) (Manley et al. 2004) – the 5 cm depth corresponds roughly with the maximum depth reachable by dabbling ducks foraging in sediment (e.g. mallard *Anas platyrhynchos* average bill length is 4.2cm in males, 3.9cm in females after Baldassarre 2014). To make our seed availability data comparable to North American studies that used soil corers 10 cm in diameter and 10 cm deep (i.e. 784.4 cm^3, 78.5 cm^2, Manley et al. 2004), we randomly selected a core from each field in each sampling period and double-sampled it, giving a 0-5 and 5-10 cm stacked sample from a single hole. In fields where straw was burned we took 9 samples in the rows where straw was concentrated by the combined harvester and subsequently burned, and another 9 samples from the rows largely devoid of burned material. This protocol was also used in the three fields where the farmer disked several bands of chopped stubble for hunting purposes. 502 and 1,358 core samples were collected and processed from the 2012–2013 and 2013–2014 winter seasons respectively.

Laboratory procedures and seed depletion rates

Core samples were frozen immediately following collection and remained frozen until processing. They were then sieved to 300 μm in accordance with the smallest space between duck bill lamellae (eg. in eurasian teal *Anas crecca*, Thomas 1982). Soil and organic matter were separated from seeds, which were then oven-dried at 70°C for 24 hours. Each seed was identified to the species and counted using a binocular magnifier (W-PI 10x/23) and reference literature (Cappers et al. 2006). Red rice (*Oryza sativa* var.) was differentiated from cultivated rice by shape (round vs long) or by manually removing the endosperm and counting the white and red grains. Only fully intact rice and weed seeds were counted and included in the analyses.

The number of seeds per species was transformed into biomass using the LEDA database (see Kleyer et al. 2008) and a reference publication (Arzel et al. 2007), along with an unpublished Camargue database (data provided by A.-L. Brochet and J.-B. Mouronval). When species mass was not available (e.g. for rare unidentified species), a sample of seeds was weighed to the nearest 0.1 mg.

Because seeds degrade and decrease in mass over the course of winter (Nelms and Twedt 1996), we devised a greenhouse experiment to test the rates of deterioration of cultivated rice and the three principal rice weeds (*Oryza sativa* var., *Bolboschoenus maritimus*, *Echinochloa* sp.), and found that seed mass decreased at rates that vary under dry and flooded conditions (Pernollet et al. in prep). While dry seed masses from the literature were used for samples collected during early winter, a correction factor derived from our experiment (mean seed mass decrease for each of the four species in dry or flooded conditions) was applied to the four tested plant species from the mid- and late winter sampling periods (i.e. cultivated rice, -16% to -64%, red rice, -7% to -52%, etc). Mean rates of seed mass decrease for the three weed species tested in the greenhouse were applied to the untested weed seed plant species identified in the samples (i.e. -11% to -37%) (details in Pernollet et al. in prep). After

applying the corrections, the resulting masses of rice and weed seeds per core sample were converted to kilograms per hectare for analysis.

Because samples were not necessarily taken at the exact same spot within the fields across sampling occasions, seed depletion was analysed at the field level rather than for each core. We sampled 52 fields over two separate time periods (early to mid-, and mid- to late winter), giving a sample size of 104. Because the time interval between sampling sessions varied (14 to 56 days early to mid-winter, 51 to 64 days mid- to late winter), we computed the daily mass loss rate per field separately for rice and weed seeds based on changes in seed mass and time elapsed between successive samples, and divided this by the initial mean seed density in that field to obtain a rate expressed as the proportional loss of seed mass per day (hereafter seed depletion rate). If the average seed density at t+1 was greater than at t, owing to variance in seed distribution within the field, seed depletion rate could be negative. Seed depletion rate could not be calculated for rice in four fields because the initial seed mass was zero, thus the final sample size for rice was 100 instead of 104.

Nocturnal waterfowl surveys

Duck surveys were conducted weekly from 19 November 2013 to 26 February 2014 (except for two weeks around Christmas) on 34 of the 37 fields where soil samples were taken during the second winter (3 fields could not be counted due to inaccessibility), and on an additional 12 adjacent fields where agricultural practices were known – these 12 were not sampled for seed density and so were excluded from models where seed density was used as a potential fixed factor. Two consecutive nights of counting each week allowed all 46 fields to be counted 13 times across the winter, except for on 1 farm with 9 fields where access difficulties permitted only 7 counts per field. Counts were done between 10:00 pm and 02:00 am (peak foraging period for dabbling ducks in Camargue, Tamisier and Dehorter 1999), with the order fields were visited being shifted each time to avoid potential time biases. Surveys were performed by walking along field edges to flush birds and count them in flight using a 4x light amplifier (Thomson, TRT Defense, see also Guillemain et al. 2002). Identification of ducks (and other waterbird species) was often aided by recognition of species-specific alarm calls. When individuals could not be identified to the species, they were recorded to the genus or family level, e.g. *Anas sp*. Stopping regularly to scan the field with the light amplifier ensured that birds reluctant to flush were not absent from our counts. Upon flushing, attention was paid to the direction the birds flew to avoid double counting them in adjacent fields. Birds detected flying overhead were not counted unless they were seen taking flight from one of the surveyed fields.

Agricultural management techniques observed on each field were recorded during each nocturnal count (e.g. plowed, disked, etc.). Water levels of flooded fields were recorded three times between November and February, on the day preceding or following nocturnal surveys by measuring depth to the nearest millimeter at 5 points on each field diagonal. Mean water levels associated with the corresponding nocturnal survey were used in the analyses. Daily rainfall records taken at the Tour du Valat and Réserve Naturelle Nationale de Camargue (Chauvelon, Tour du Valat, unpublished data) for the same period were used to determine unintentional flooding due to rain on dry rice fields.

We defined five water levels (dry, rain, low, medium, high) based on recent precipitation and the water depths known to provoke different feeding postures in eurasian teal and mallard (*postures,* from Thomas, 1982). “Dry” fields were not intentionally flooded and did not

receive heavy rain (< 30 mm) the week before the survey; "rain" corresponded to fields left dry by farmers but which received heavy rain during the week preceding the survey (cumulative rainfall ≥ 30 mm, *dabbling*); "low" corresponded to intentionally flooded fields where measured water depth was less than 5cm (*dabbling*); "medium" corresponded to intentionally flooded fields where measured water depth ranged between 5 (inclusive) and 10 cm (*head under*); "high" corresponded to intentionally flooded fields where measured water depth was at least 10 cm (*dipping or upending*). We calculated field areas and the distance (km) of each field from the nearest potential duck day roost site using Geoportail (http://www.geoportail.gouv.fr/accueil).

Statistical analyses

The seed bank was described for each sampling period, and included the average density (kg/ha) and abundance of seeds (number of seeds) of all species across all cores and fields. Because the number of seed species increased with increasing number of cores within a field, species occurrence (proportion of fields where a given species occurred, at each sampling date) was computed by pooling the list of species from all cores from each field and computing the percentage of fields containing a given species. Total rice and weed depletion across the winter was expressed as a percentage. The dabbling duck community was described as the mean density of birds per species recorded during a weekly nocturnal survey, pooling all surveyed fields and averaging over the number of weeks of the study.

We used generalized linear mixed-effects models (GLMM) to assess the variables influencing initial rice and weed seed availability, rice and weed seed depletion rate, and field use by duck. Starting with a full model including all possible 2-way interactions, we used the Akaike's Information Criterion (AIC) for model selection (Burnham and Anderson 2002). All models were tested and only a suite of candidate models whose AIC was lower than the null model are presented in the result tables. We ranked models by AIC, and to better interpret the relative likelihood of a given model we computed the Akaike weight (w_i, the weight of evidence in favour of model "i") for each model. Finally, we calculated the relative importance of each explanatory variable by summing w_i for all models containing that variable (Burnham and Anderson 2002). We used model averaging to extract parameter estimates (SE and 95% CI) from the best models ($\Delta AIC < 2$) (Function model.avg of package MuMIn), and when a significant effect was detected (deviance test, $P < 0.05$) we performed pair-wise comparisons of means using Tukey's post hoc test to determine which categories differed from each other (procedure details in Burnham and Anderson 2002).

In testing the variables explaining initial post-harvest rice and weed seed availability, it was necessary to exclude from the analysis eight fields that suffered heavy damage from wild boar [*Sus scrofa*] and consequently had low yields (averages of 3 t/ha -range 1.5 to 4.5- compared to 5.12 t/ha in other fields) and large quantities of waste rice. These fields had the same cultivation historic and post-harvest straw management, so that including them in the analysis of the straw management procedures would have inflated the potential effect of the latter factors. However, these fields were included in analyses of seed depletion rate – since this was corrected for initial seed density – and duck use.

Function *lmer* of package *lme4* (Bates et al. 2014) and a Gaussian distribution were used for the analyses of seed availability. Seed densities per core (kg/ha – rice and weed seeds considered separately) were log-transformed to get model residuals closer to normal distribution. Several transformations were tested on the seed depletion rate, but the log-

transformation did not improve the distribution of the residuals and the Arcsine transformation was not possible due to negative seed loss values. GLMM however is robust enough to support such non normality (Zuur et al. 2010), so the analyses were run with the raw data. Field number, farm identity and year were tested as random factors in the seed availability analysis. To explain initial rice and weed seed availability (early winter), we considered the following as fixed variables: weed seed density (to explain variation in rice seed density), rice seed density (to explain variation in weed seed density), straw management (chopping, disking, burning, with cores of burned and unburned lines of the same field first considered together and then separately), type of farming (organic or conventional), and number of years cultivated in rice. Number of years cultivated in rice was treated as a continuous variable. The only interaction considered in the analyses was between number of years in rice cultivation and type of farming.

To explain seed depletion rate we considered the following as fixed variables: the sample period (first: early to mid-winter, second : mid- to late winter), initial mean seed density (rice and weed seeds) per core sample at the beginning of the corresponding sample period, agricultural practices employed during that period (disked, plowed, none) and winter flooding. In fact, once the straw of a field had been chopped, burnt or disked during or right after harvest, three post-harvest practices were distinguished in the depletion analysis: “disked”, “plowed”, or “none”, depending on what the farmer did between two soil sampling sessions. Finally, for this analysis winter flooding was considered a binary variable (Y/N).

Function *glmmadmb* of package *glmmADMB* (Fournier et al. 2012) was used to apply a negative binomial distribution to the duck data, which were over-dispersed. The total number of dabbling ducks recorded in each field during each weekly survey was used as the response variable. The field area (ha) was used as an offset term in the GLMM (field size ranged from 1.24 to 6.91 ha) (Yan et al. 2009). Field number, farm identity and week of survey were tested as random factors. To explain the number of ducks per field we considered the following as fixed variables: total seed availability (rice plus weeds, kg/ha), water level (dry, rain, low, medium, high), straw management (burning, chopping, disking, chopping-disking or plowing) and distance from the field to the nearest potential diurnal roost (km). Using the seed mass depletion rates described above, we extrapolated seed availability from the core samples and the number of days elapsed since the last seed sampling session. We used Log-transformed seed density because we expected seed density to influence bird use following a log-normal relationship (cf. Anteau et al. 2011).

All statistical tests were performed using R version 3.1.3 (R Core Team 2013). Data are presented as mean ± standard error (SE) throughout the paper.

We evaluated carrying capacity (DUDs) of Camargue rice fields immediately following harvest for two scenarios – the actual, where 9% of rice fields are winter flooded (Pernollet et al. 2015), and a hypothetical, where all rice fields are winter flooded. For the latter we calculated possible DUDs as the total available energy in the area (available food [g dry mass] times the metabolizable energy of this food [kcal/g dry mass]) divided by the daily energy requirements of an individual bird [kcal/day/duck]. DUD was calculated based on the total initial density of rice and the main three weed seeds (red rice *Oryza sativa* var., *Echinochloa* spp., and *Bolboschoenus maritimus)* multiplied by their respective metabolizable energy contents: 3.34 kcal/g for rice and red rice (true metabolizable energy, Reinecke et al. 1989), 2.75 kcal/g for *Echinochloa* spp. (true metabolizable energy, Checkett et al. 2002) and 3.12 kcal/g for *Bolboschoenus maritimus* (considering a 70% assimilation efficiency and total

energy density, Legagneux 2007). For these calculations, winter consisted of 120 days and daily energy requirement was 285 kcal per individual, based on mallard ducks (Prince 1979).

RESULTS

Initial seed bank

A total of 111 seed species were identified in 1,860 core samples collected from 52 rice fields over two winters that could be analysed (See Appendix 1 for details on mean seed number, density and species occurrence). An average of 349.9 kg/ha (± 57.6 SE, *n* = 52 fields) of rice seeds were left in the fields after harvest. Weed seed densities averaged 141.6 kg/ha (± 21.3 SE, *n* = 52) in the studied fields, with three species representing 82% of the mean weed seed density. Of the total mean seed density, 47% was red rice (*Oryza sativa* var.), 25% *Echinochloa* spp., and 10% *Bolboschoenus maritimus*. Rice grains were the most abundant seeds in all sampling periods. However, rice seed density gradually decreased across the season, to 146.7 kg/ha (± 27.5 SE, *n* = 52) in mid-winter and 38.1 kg/ha (± 11.5 SE, n = 52) in late winter. The mean density of weed seeds also gradually decreased to 70.3 kg/ha (± 8.8 SE, *n* = 52) in mid-winter and 44.5 kg/ha (± 5.7 SE, *n* = 52) in late winter (Fig. 2). Mean rice density decreased on average by 311.8 kg/ha (89%) from early to late winter, and weed density by 97.0 kg/ha (69%).

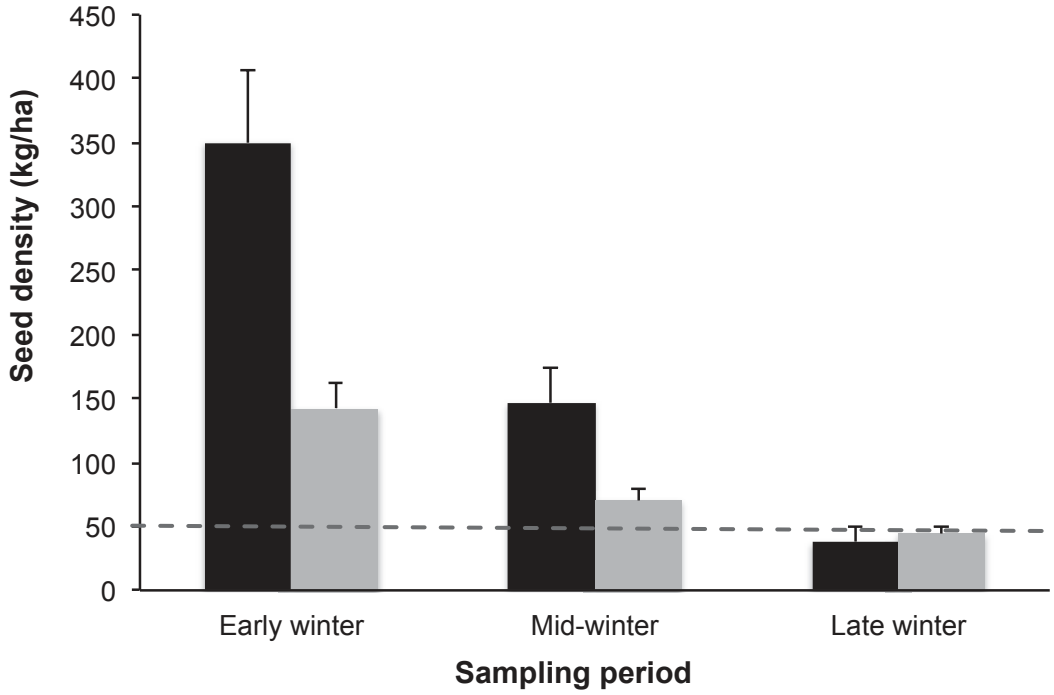

Figure 2. Average rice and weed seed densities (black and grey columns, respectively) in the 52 Camargue rice fields surveyed three times a season over two winter seasons (2012–2013, *n* = 16 and 2013–2014, *n* = 36). Vertical bars represent standard errors. The horizontal dashed line at 50 kg/ha represents the theoretical Giving-Up Density below which waterfowl should cease foraging in rice fields, after Reinecke et al. (1989) and Geer et al. (2009).

Factors influencing initial seed densities

The total seed mass immediately following harvest was highly variable across samples from a single field (maximum range 131.3 kg/ha to 9,582.9 kg/ha after extrapolation from two core samples from the same field), as well as from one field to another (maximum range 51.6 kg/ha ± 10.8 SE and 2,712.6 kg/ha ± 1,144.4 SE in two fields, $n = 9$ cores in both cases).
Table 2 shows the 22 models that were significantly better than the null model at explaining the variation in rice seed density per core collected immediately following harvest. Among these models, four factors and two interactions stood out as the most important as judged from cumulative AIC weights: log(weed seed density) (relative importance, cumulative AIC weight = 1.00), number of years the field had been cultivated in rice (1.00), farming type (0.37), straw management procedure (0.16), the interaction between log(weed seed density) and number of years the field had been cultivated in rice (0.28), and the interaction between number of years the field had been cultivated in rice and type of farming (0.12). Based on ΔAIC values, three models performed better than the others at explaining variation in rice seed density per core sample. All three included effects of weed seed density and the number of years the field had been cultivated in rice, one included the interaction between the log(weed seed density) and the number of years the field had been cultivated in rice, and another included type of farming instead of the interaction (Table 2). Taken together, the three best models accumulated 68% of AIC weight. These showed a significant positive relationship between log(rice seed density) and log(weed seed density) in the same core (Model averaged estimate: $\beta = 0.53 \pm 0.11$ SE), while the other model-averaged estimates were non-significant (Table 7). Notably, no significant difference in early winter rice density was observed between fields where straw was burned, chopped or disked. However, in fields where straw was burned there were significantly more rice grains in the burned lines than in unburned lines of the field (burned fields: log(rice density)~straw management +(1|field.fac)+(1|farm.fac), $\beta = -0.60 \pm 0.18$ SE, $P = 0.001$).

Table 3 shows that 24 models were significantly better than the null model at explaining variation in log(weed seed density) immediately following harvest. Among these models, four factors and two interactions stood out as the most important as judged from cumulative AIC weights: number of years the field had been cultivated in rice (cumulative AIC weight = 1.00), log(rice seed density) (0.99), type of farming (0.84), straw management procedure (0.42), the interaction between number of years the field had been cultivated in rice and type of farming (0.79), and the interaction between log(rice seed density) and number of years the field had been cultivated in rice (0.27).

Based on ΔAIC values, three models performed better than the others at explaining variation in weed seed density per core sample. All three included effects of rice seed density in the same core, the number of years the field had been cultivated in rice, the type of farming, and the interaction between number of years the field had been cultivated in rice and farming type. One model also included the straw management procedure, and another included the interaction between log(rice seed density) and number of years the field had been cultivated in rice (Table 3). Taken together, the three best models accumulated 71% of AIC weight. These showed a significant positive relationship between log(weed seed density) and log(rice seed density) in the same core (Model averaged estimate: $\beta = 0.07 \pm 0.01$ SE), a lower density of weed seeds in the organic fields than conventional fields (Model averaged estimate for Organic: $\beta = -2.50 \pm 0.88$ SE), and a positive relationship between log(weed seed density) and the interaction between number of years the field had been cultivated in rice and type of farming (Model averaged estimate for Organic: $\beta = 1.51 \pm 0.51$ SE). No significant difference

in weed seed density was observed in fields where straw was burned, chopped or disked (Table 7). In contrast to what was observed for rice grains, in fields where straw was burned there were not significantly more weed seeds in the burned rows than unburned rows (log(weed seed density)~straw.fac+(1|field.fac)+(1|farm.fac), P= 0.53).

Table 2. Candidate models, numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and Akaike model weight (w_i) used to determine what influences Log(mean rice seed density per core sample) in rice fields during early winter (immediately following harvest) for winters 2012–2013 and 2013–2014 in Camargue, France. Log(Weed seed density) (kg/ha) in the same core sample, Years of rice = number of consecutive years this field had already been cultivated in rice, Farming type = conventional vs. organic, Straw = method of straw disposal (burning, chopping, disking) and possible interactions. Random factors: Year = winters 2012–2013 vs. 2013–2014, Field number and Farm identity.

Parameters	K	AIC	ΔAIC	w_i
Log(Weed seed density) + Years of rice	2	2516.51	0.00	0.38
Log(Weed seed density) + Years of rice + Log(Weed seed density) x Years of rice	3	2518.33	1.82	0.15
Log(Weed seed density) + Years of rice + Farming type	4	2518.35	1.84	0.15
Log(Weed seed density) + Years of rice + Farming type + Years of rice x Farming type	5	2519.77	3.26	0.07
Log(Weed seed density) + Years of rice + Straw	5	2519.85	3.34	0.07
Log(Weed seed density) + Years of rice +Farming type+ Log(Weed seed density) x Years of rice	5	2520.21	3.70	0.06
Log(Weed seed density) + Years of rice + Farming type + Straw	7	2521.46	4.95	0.03
Log(Weed seed density) + Years of rice +Farming type + Log(Weed seed density) x Years of rice + Years of rice x Farming type	6	2521.66	5.15	0.03
Log(Weed seed density) + Years of rice +Straw + Log(Weed seed density) x Years of rice	6	2521.74	5.24	0.03
Log(Weed seed density) + Years of rice +Farming type + Straw + Years of rice x Farming type	8	2523.14	6.63	0.01
Log(Weed seed density) + Years of rice + Farming type + Straw + Log(Weed seed density) x Years of rice	8	2523.38	6.87	0.01
Log(Weed seed density) + Years of rice +Farming type + Straw + Years of rice x Farming type + Log(Weed seed density) x Years of rice	9	2525.08	8.57	0.01
Years of rice	1	2538.34	21.84	0.00
Years of rice + Farming type	3	2539.48	22.97	0.00
Years of rice +Farming type + Years of rice x Farming type	4	2540.04	23.53	0.00
Years of rice + Straw	4	2541.64	25.13	0.00
Years of rice + Farming type + Straw	6	2542.76	26.25	0.00
Years of rice + Farming type + Straw + Years of rice x Farming type	7	2543.43	26.92	0.00
Log(Weed seed density)	1	2615.20	98.69	0.00
Log(Weed seed density) + Farming type	3	2616.72	100.21	0.00
Log(Weed seed density) + Straw	4	2618.27	101.77	0.00
Log(Weed seed density) + Farming type + Straw	6	2619.62	103.11	0.00

Table 3. Candidate models, numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and Akaike model weight (w_i) used to determine what influences Log(mean weed seed density per core sample) in rice fields during early winter (immediately following harvest) for winters 2012–2013 and 2013–2014 in Camargue, France. Log(Rice seed density) (kg/ha) in the same core sample, Years of rice = number of consecutive years this field had already been cultivated in rice, Farming type = conventional vs. organic, Straw = method of straw disposal (burning, chopping, disking) and possible interactions. Random factors: Year = winters 2012–2013 vs. 2013–2014, Field number and Farm identity.

Parameters	K	AIC	ΔAIC	wi
Log(Rice seed density) + Years of rice + Farming type + Years of rice x Farming type	5	1355.22	0.00	0.36
Log(Rice seed density) + Years of rice +Farming type + Straw + Years of rice x Farming type	8	1356.26	1.04	0.21
Log(Rice seed density) + Years of rice +Farming type + Log(Rice seed density) x Years of rice + Years of rice x Farming type	7	1357.17	1.94	0.14
Log(Rice seed density) + Years of rice +Farming type + Straw + Years of rice x Farming type + Log(Rice seed density) x Years of rice	9	1358.22	3.00	0.08
Log(Rice seed density) + Years of rice + Straw	5	1358.54	3.32	0.07
Log(Rice seed density) + Years of rice	2	1359.37	4.15	0.05
Log(Rice seed density) + Years of rice +Straw + Log(Rice seed density) x Years of rice	6	1360.52	5.30	0.03
Log(Rice seed density) + Years of rice + Farming type + Straw	7	1360.54	5.32	0.03
Log(Rice seed density) + Years of rice + Log(Rice seed density) x Years of rice	3	1361.34	6.12	0.02
Log(Rice seed density) + Years of rice + Farming type	4	1361.37	6.15	0.02
Log(Rice seed density) + Years of rice + Farming type + Straw + Log(Rice seed density) x Years of rice	8	1362.52	7.30	0.01
Log(Rice seed density) + Years of rice +Farming type+ Log(Rice seed density) x Years of rice	5	1363.34	8.12	0.01
Years of rice +Farming type + Years of rice x Farming type	4	1377.19	21.97	0.00
Years of rice + Farming type + Straw + Years of rice x Farming type	7	1377.89	22.67	0.00
Years of rice + Straw	4	1381.05	25.83	0.00
Years of rice	1	1382.32	27.10	0.00
Years of rice + Farming type + Straw	6	1383.03	27.81	0.00
Years of rice + Farming type	3	1384.32	29.10	0.00
Log(Rice seed density) + Straw	4	1400.49	45.27	0.00
Log(Rice seed density)	1	1402.26	47.03	0.00
Log(Rice seed density) + Farming type + Straw	6	1402.45	47.22	0.00
Log(Rice seed density) + Farming type	3	1404.24	49.02	0.00
Straw	3	1418.42	63.20	0.00
Farming type + Straw	4	1420.33	65.10	0.00

Seed depletion rate across the winter

Table 4 shows the 12 models that were significantly better than the null model at explaining rice depletion rate. Among these models, four factors stood out as the most important as judged from cumulative AIC weights: average seed density (rice and weed seeds) per field at the beginning of the corresponding time period (cumulative AIC weight = 0.91), agricultural practice applied during that period (0.83), time periods (0.30), and winter flooding (0.30). Based on ΔAIC values, three models performed better than the others at explaining variation in rice depletion rate. All three included effects of seed density in the field at the beginning of the corresponding time period and the agricultural practice applied during that period. One also included winter flooding, while another included the time period (Table 4). Taken together, the three best models accumulated 69% of AIC weight. These showed a significant positive relationship between rice depletion rate and seed density in the field at the beginning of the corresponding time period (Table 7). Applying the Tukey post-hoc test three times to each of the three best models showed that rice depletion rate was higher in plowed fields than in stubble fields or fields that did not receive any agricultural treatment during a given time interval ("none" compared to "plowed" in the three models: $P = 0.022$, $P = 0.020$, $P = 0.0224$, respectively, Fig. 3).

Table 4. Candidate models, numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and Akaike model weight (w_i) used to determine what influences rice depletion rate during winters 2012–2013 and 2013–2014 in Camargue, France. Period = early to mid-winter or mid to late winter; Seed density = average density of seeds (rice + weed) per field at the beginning of the corresponding time period; Practice = the agricultural practice applied during that period, i.e., partially-disked, disked, plowed, none; and Flooding = winter flooding vs. no flooding. Random factors: Year = winter 2012–2013 vs. 2013–2014, Field number and Farm identity.

Parameters	K	AIC	ΔAIC	wi
Seed density + Practice	5	-513.89	0.00	0.39
Seed density + Practice + Flooding	7	-512.07	1.82	0.16
Seed density + Practice + Period	7	-512.01	1.88	0.15
Seed density	1	-510.88	3.01	0.09
Seed density + Practice + Flooding + Period	10	-510.20	3.69	0.06
Seed density + Flooding	3	-509.33	4.56	0.04
Seed density + Period	3	-508.88	5.01	0.03
Practice	4	-508.30	5.59	0.02
Seed density + Practice	5	-508.17	5.71	0.02
Seed density + Flooding + Period	5	-507.33	6.55	0.01
Practice + Flooding + Period	8	-507.13	6.76	0.01
Practice + Flooding	6	-507.08	6.81	0.01

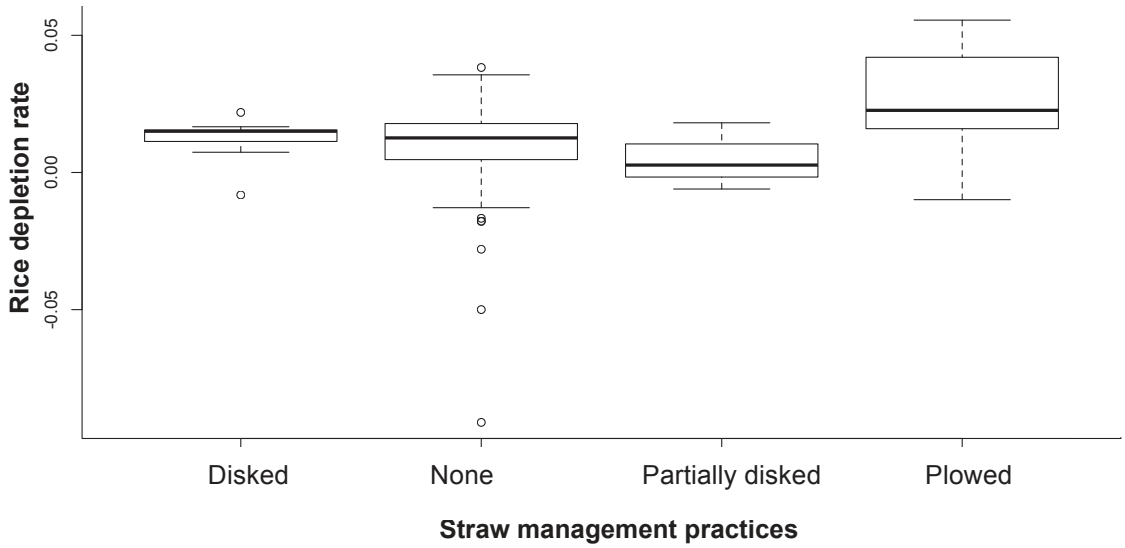

Figure 3. Average rice and weed depletion rates (proportion of change per day) for each agricultural practice in the 52 studied Camargue rice fields for winter 2012–2013 (n = 16) and 2013–2014 (n = 36). The figure represents the minimum, the first quartile, the median, the third quartile, and the maximum. Post-hoc Tukey tests at $P < 0.05$ indicated that depletion rates of rice were greater in plowed fields than in stubble fields or fields with no agricultural treatments ("None"). There were no significant differences between the other treatments (see text).

Table 5 shows that 12 models explained weed seed depletion rate significantly better than the null model. Among these models, four factors stood out as the most important as judged from cumulative AIC weights: average seed density (rice and weed seeds) per field at the beginning of the corresponding time period (cumulative AIC weight = 0.98), time periods (0.56), agricultural practice applied during that period (0.46), and winter flooding (0.28). Based on ΔAIC values, six models explained variation in weed seed depletion rate better than the others. All six models included effects of seed density in the field at the beginning of the corresponding time period, alone or in combination with some of the other factors (Table 5). Taken together, the six best models accumulated 86% of AIC and showed a significant positive relationship between weed seed depletion rate and seed density at the beginning of the corresponding time period (Table 7). The Tukey post-hoc tests applied to each of the six best models including agricultural practices showed that weed seed depletion rate was not significantly different for any agricultural treatments (data not shown).

Nocturnal waterfowl densities

Mallards and eurasian teal were the most numerous waterfowl species recorded during the surveys (69.5 % ± 5.6 SE and 25.5 % ± 4.8 of total bird numbers on average, respectively, n = 13 weekly counts), followed by pintail *Anas acuta*, gadwall *Anas stepera* and northern shoveler *Anas clypeata* (4.2 % ± 2.0 SE, 0.7 % ± 0.4 SE and 0.1 % ± 0.03 SE, respectively). Unidentified dabbling ducks comprised 9.0 % ± 3.4 SE of the 16,347 individual detections. Mean densities of each duck species are shown in Fig. 4.

Table 5. Candidate models, numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and Akaike model weight (w_i) used to determine what influences weed depletion rate during winters 2012–2013 and 2013–2014 in Camargue, France. Period = early to mid-winter or mid- to late winter; Seed density = average density of seeds (rice + weed) per field at the beginning of the corresponding time period; Practice = the agricultural practice applied during that period, i.e., partially-disked, disked, plowed, none; and Flooding = winter flooding vs. no flooding. Random factors: Year = winter 2012–2013 vs. 2013–2014, Field number and Farm identity.

Parameters	K	AIC	ΔAIC	wi
Seed density + Practice + Flooding	7	-682.46	0.00	0.20
Seed density	1	-682.35	0.11	0.19
Seed density + Period	3	-682.34	0.12	0.19
Seed density+ Practice	5	-681.58	0.89	0.13
Seed density + Flooding	3	-680.60	1.86	0.08
Seed density + Practice + Flooding + Period	9	-680.52	1.94	0.08
Seed density + Period + Flooding	5	-680.45	2.02	0.07
Seed density + Practice + Flooding	7	-679.58	2.89	0.05
Practice + Period	6	-676.17	6.29	0.01
Practice + Period + Flooding	8	-675.43	7.03	0.01
Period	2	-675.07	7.39	0.00
Period + Flooding	4	-673.14	9.32	0.00

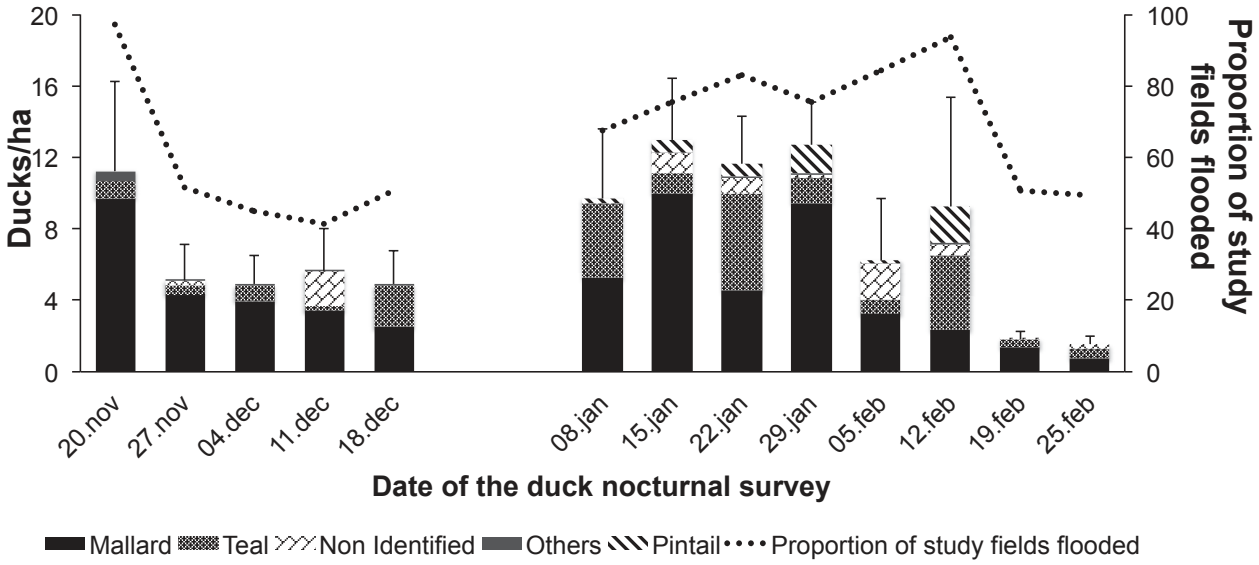

Figure 4. Weekly average densities of duck observed per species in the 46 rice fields surveyed for nocturnal duck use over the winter 2013–2014, and weekly proportion of all study fields flooded (dotted line). "Other" includes Gadwall, Northern Shoveler and Common Shelduck, Error bars represent standard errors.

Apart from dabbling ducks, two other waterfowl species, common shelduck *Tadorna tadorna* and greylag goose *Anser anser* were observed (ten individuals over three nights and nine individuals over three nights, respectively), as well as an assortment of other waterbirds (Other waterbirds: common snipe *Gallinago gallinago* (44%), *Tringa* and *Calidris* sp. (24%), northern lapwing *Vanellus vanellus* (16%), greater flamingo *Phoenicopterus roseus* (7%), grey heron *Ardea cinerea* (5%), laridae (2%), common crane *Grus grus* (2%), eurasian curlew *Numenius arquata* (1%) and little egret *Egretta garzetta* (0.1%)).

Table 6 shows the 15 models that were significantly better than the null model at explaining the number of ducks in post-harvest rice fields. Among these models, four factors stood out as the most important as judged from cumulative AIC weights: water level (cumulative AIC weight = 1.00), straw management (0.77), distance from the field to the nearest potential diurnal roost (km) (0.49), and log(seed density) (0.28). Based on ΔAIC values, four models performed better than the others at explaining variation in the number of ducks per field. All four included water level, three included straw management, two included distance to the nearest potential duck day-roost, and one included log(seed density) (Table 6). Taken together, the four best models accumulated 85% of AIC weight. Ducks were significantly more numerous in flooded than in dry fields, regardless of water level (weekly average: flooded: 23.5 ducks/ha ± 2.3 SE; dry: 0.3 ± 0.1 SE. *n* = 13 weeks in both cases; see also Fig. 5 and model averaged estimates in Table 7). Duck numbers were significantly lower in rice fields where straw was burned compared to those where straw was disked, chopped, or chopped and partly disked (Table 7).

Table 6. Candidate models, numbers of parameters (K), Akaike's Information Criterion (AIC) difference from lowest AIC value (Delta AIC), and Akaike model weight (w_i) used to determine what influenced the number of ducks counted in post-harvest rice fields across winters 2013–-2014, Camargue, France. Water level = dry, rain, low, middle, high water level; Straw = method of straw disposal (burning, chopping, chopping - disking, disking, plowing); Roost = Distance (km) to the nearest potential roosting site; Log (Seed density) = Log(seed density, rice + weed seed density, kg/ha) in the field. Random factors: Week of survey, Field number and Farm identity.

Parameters	K	AIC	ΔAIC	wi
Water Level + Straw	10	877.44	0.00	0.35
Water Level + Straw + Roost	11	878.54	1.11	0.20
Water Level + Roost	6	879.03	1.60	0.16
Water Level + Straw + Log (Seed density)	11	879.16	1.73	0.15
Water Level + Straw + Log (Seed density) + Roost	12	880.50	3.06	0.08
Water Level + Log (Seed density) + Roost	7	881.03	3.59	0.06
Water Level	5	884.66	7.23	0.01
Water Level + Log (Seed density)	6	886.63	9.19	0.00
Straw + Roost	6	929.28	51.84	0.00
Straw	5	929.67	52.23	0.00
Straw + Log (Seed density)	6	931.12	53.68	0.00
Straw + Log (Seed density) + Roost	7	931.65	54.21	0.00
Roost	1	947.32	69.88	0.00
Log (Seed density) + Roost	2	949.17	71.74	0.00
Log (Seed density)	1	949.49	72.06	0.35

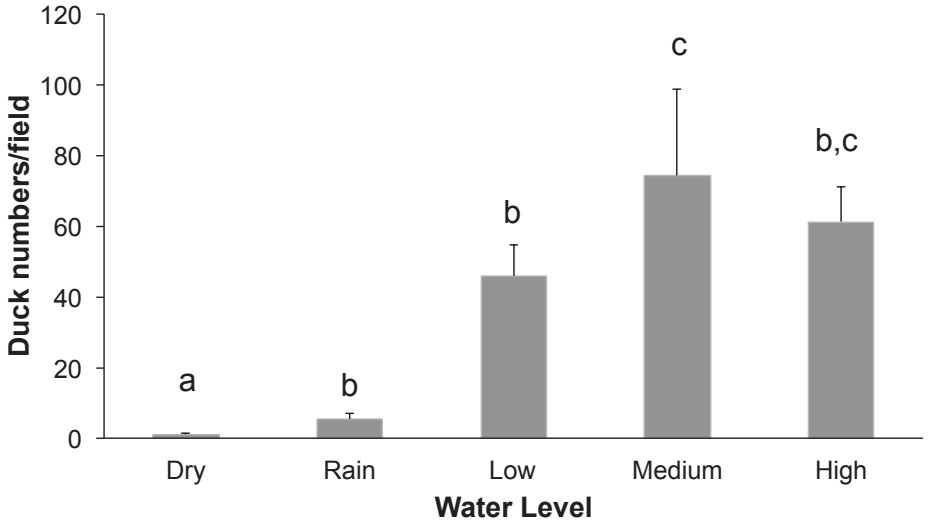

Figure 5. Mean number of ducks per ricefield during the survey week depending on water levels over the winter 2013–2014 in Camargue, France. Vertical bars represent standard errors. Columns with different letters differed significantly after post hoc Tukey tests.

Table 7. Model-averaged parameter estimates, standard-errors and 95% confidence intervals of the variables present in models with Δ AIC <2 to explain rice and weed seed initial density values immediately following harvest, rice and weed seed depletion rates in the post-harvest rice fields in the Camargue, winter 2012–2013 and 2013–2014, and duck numbers counted in the post-harvest rice fields in the Camargue, winter 2013–2014. The value of parameter estimates, standard-errors and 95% confidence intervals of the variables present in models for seed depletion rates were multiplied by 10 000 for easier reading. We considered coefficient estimates with 95% CI that did not overlap zero to be significant.

Variable	Estimate	SE	95% confidence interval Lower	Upper	Cumulative AIC weight
Log(Rice Seed Density after harvest)					
Log(Weed seed density)	0.53	0.11	0.32	0.73	1.00
Years of rice	0.007	0.02	-0.04	0.05	1.00
Farming type (Organic)	0.06	0.59	-1.10	1.22	0.37
Log(Weed seed density) x Years of rice	-0.004	0.009	-0.02	0.01	0.28
Log(Weed Seed Density after harvest)					
Log(Rice seed density)	0.07	0.01	0.04	0.10	0.99
Years of rice	-0.01	0.01	-0.04	0.02	1.00
Farming type (Organic)	-2.50	0.88	-4.22	-0.78	0.84
Years of rice x Farming type (Organic)	1.54	0.51	0.54	2.55	0.79
Straw.Management					
(Chopped	-0.40	0.24	-0.87	0.07	0.16
Disked)	-0.34	0.29	-0.91	0.22	
Log(Rice seed density) x Years of rice	0.0003	0.001	-0.002	0.003	0.27
Rice depletion rate (*10 000)					
Seed density	0.20	0.06	0.07	0.32	0.91
Practice					0.83
(None	-55.02	56.70	-167.66	57.61	
Partially disked	-69.51	111.2	-290.46	151.44	
Plowed)	107.7	75.99	-43.30	258.62	
Flooding: (Yes)	31.59	46.80	-61.41	124.59	0.30
Period: Intercept (Mid-late winter)	-9.56	38.71	-86.48	67.36	0.30
Weed depletion rate (*10 000)					
Seed density	0.11	0.03	0.05	0.16	0.98
Period (Mid-late winter)	-25.56	17.85	-60.97	9.88	0.56
Practice					0.46
(None	-30.60	19.92	-83.10	21.90	

Partially disked	-2.65	54.39	-105.34	110.65	
Plowed)	23.79	35.08	-45.86	93.44	
Flooding: (Yes)	-15.06	19.92	-54.61	24.48	0.28
Duck numbers					
Water level					1.00
(Rain	2.61	0.56	1.50	3.72	
Low	3.12	0.51	2.12	4.13	
Medium	5.09	0.65	3.80	6.38	
High)	5.14	1.17	5.15	1.17	
Straw Management					0.77
(Chopped Disked	2.53	1.07	0.41	4.64	
Chopped	1.94	0.63	0.69	3.18	
Disked	1.62	0.63	0.38	2.85	
Plowed)	-0.61	0.94	-2.47	1.23	
Distance to the nearest roosting site	0.0007	0.0005	-0.0002	0.002	0.49
Log (Seed density)	0.24	0.45	-0.65	1.12	0.28

Camargue carrying capacity of wintering ducks

The average seed density at the beginning of the winter was 465.6 g/ha (five most abundant seed species), which would represent 1,531,308.4 kcal/ha. Given that mallards require 285 kcal per day per individual, an average Camargue ricefield at the beginning of the winter could theoretically host 5,373 DUDs/ha. In a theoretical winter season of 120 days, during which no mechanism for seed depletion exists other than foraging ducks, the carrying capacity would be 45 mallard-sized ducks per hectare per day. Considering that approximately 10,000 ha in Camargue are cultivated in rice-rice rotation and 9% of these are flooded and are thus available to ducks, the region could therefore accommodate 4,835,700 duck.days, i.e. 40,297 ducks per day on average. If all fields in rice-rice rotation were to be flooded, the carrying capacity would increase to 53,730,000 duck.days, i.e. 447,750 ducks per day on average.

DISCUSSION

Residual rice and weed seeds were abundant in Camargue rice fields immediately following harvest, but quickly disappeared as winter progressed. Nocturnal surveys indicated that ducks readily use flooded rice fields as foraging grounds.

Post-harvest rice and weed seed densities were highly variable both within and between fields, and so were hardly predictable. Immediately following harvest we measured an average of 350 kg/ha of rice in the first 5 cm of soil. Farmers reported an average yield of 4,769 kg/ha in the 52 studied fields. Our seed samples suggest that yield loss in these fields averaged 7.9% (± 1.5 SE), which was consistent with the 8.7% reported by Manley et al. (2004) in the Mississippi Alluvial Valley (MAV hereafter) and slightly greater than the 3–6% reported by Eadie et al. (2008), in which data was assessed from all relevant US studies. However, when the 8 fields that suffered wild boar damage were excluded from the calculation, yield loss here dropped to 4.8% (± 0.8 SE, n = 44 fields), within range of these American studies.

Where cores were double-sampled for inter-study comparability purposes with North American studies, the abundance and mass of seeds in the 0-5 and the 5-10 cm samples were similar, thus the average density of seeds following harvest in the first 10 cm of soil could simply be double that of the first five centimetres (i.e. 700 kg/ha for rice and 283 kg/ha for weed seeds). This average rice density falls within the upper ranges of densities reported in North American studies by Eadie et al. (2008) (134 to >600 kg/ha) and Stafford et al. (2010)

(66 to 672 kg/ha), and exceeds the ca. 250 kg/ha reported by Amano et al. (2004, 2006 in Stafford et al. 2010) in Japan. The weed seed density we recorded greatly exceeds the 3.1–7.4 kg/ha calculated by Manley et al. (2004) for the MAV, and the 4–44 kg/ha from Eadie et al. (2008), in which data was assessed from all relevant US studies. Intensive mechanical and chemical weed control in North American rice fields is considered to generally limit weed seeds to less than 50 kg/ha (Stafford et al. 2010). However, in France where access to pesticides are more limited than in the US and in other neighbouring Mediterranean countries, less effective weed control measures such as crop rotation and/or mechanical control take a greater role in curbing weed growth, and weed incursions are generally more severe as a result. Previous European studies incorporated comparatively low sampling efforts (fewer cores and study sites), and reported significantly lower seed density (rice and weeds) estimations than that of the present study (210 kg/ha seeds in Camargue (Tamisier and Dehorter 1999) and 240 kg/ha in Doñana, Spain (Toral 2011) vs a total of 492 kg/ha in the present study).

Rice and weed seed densities were positively correlated, which is contrary to the general expectation that weedy fields generate lower rice yields (e.g. Oerke 2006). However, if the ideal and so promoted growing conditions for rice also benefit weed growth, the relatively ineffective weed controls employed in Camargue would allow the rice yield and weed seed bank to fluctuate in tandem.

Many studies have investigated the influence of post-harvest practices on residual rice seed availability and accessibility to waterfowl, the majority being from the U.S. and Japan (Elphick et al. 2010b, Stafford et al. 2010). However, the extent to which straw management practices employed immediately following harvest can influence seed availability and use of fields by ducks remains uncertain (see Stafford et al. 2005 and Elphick et al. 2010, respectively). Our findings indicate that initial rice and weed seed densities were not significantly influenced by post-harvest straw management practices, except for in plowed fields where rice and weed seed depletion rates were significantly higher, a result shared with Miller et al. (1989), Anamo et al. (2006) and Lee et al. (2007). While no straw management practice had a clear effect on seed densities at the beginning of winter, the spatial distribution of rice seeds was different between fields that were burned and chopped. In burned fields the combine harvester concentrates straw – and rice, incidentally – into rows, which are subsequently burned; in fields where straw is chopped, straw and seeds are spread uniformly behind the machine. In terms of foraging efficiency, the concentration of waste rice in burned rows likely increases ducks' use of a field; burning increases foraging efficiency by improving seed access (Havens et al. 2009), even if it can also reduce quantities of waste rice by ca. 30% (Miller et al. 1989). Moreover, burned rows are likely easily located by their black color. All of this could explain why ducks preferentially selected burned fields in Havens et al. (2009). Surprisingly, we observed a lower number of ducks in rice fields where straw was burned compared to those where it was disked, chopped, or chopped and partly disked. Although beyond the scope of our analysis, it should be noted that all of the fields we surveyed that were both flooded and burned were surrounded by hedges, a landscape feature known to reduce nocturnal use of rice fields by Greater Flamingo in the same area (Tourenq et al. 2001b).

The factor that best explained nocturnal duck use of rice fields was winter flooding, be it intentional or caused by heavy rain. This is consistent with earlier results in Japan (Shimada et al. 2000, Tajiri and Ohkawara 2013), Europe (Lourenço and Piersma 2009) and the US (Day and Colwell 1998, Elphick and Oring 1998, 2003, Strum et al. 2013), and can be explained by

the need for ducks foraging for seeds on dry land to rely on water for handling their food (Guillemain et al. 1999). Beyond the local scale, ducks are reportedly more numerous in a given winter quarter when flooding is greater (Toral et al. 2011) and are even known to distribute among winter quarters at the flyway scale depending on the intensity of ricefield flooding (Pernollet et al. 2015). Elphick and Oring (2003) reported that 14 to 22 cm water depth was ideal for ducks; in our study duck numbers were greatest in fields under 5-10 cm of water, owing perhaps to the relative abundance of small Eurasian Teal in our duck community. Contrary to the results of Strum et al. (2013) in California – an arid region currently in drought – our results demonstrate that rainfall alone could provide the minimum suitable depth of 5 cm for dabbling ducks during winter in Camargue (average of 58,0 mm rain between October and February, maximum in October 90.6 mm, 1977-2006 (PNRC 2013)).
Since dabbling ducks rely heavily on water for foraging, it makes sense that we found flooding to be the primary determinant of duck numbers on rice fields, and not seed availability. Furthermore, average seed densities were high, so birds may not have been food-limited in the study area. That flooded fields attract ducks is also apparent from the high concentrations of birds we detected during nocturnal surveys (2,400 birds/km²) compared to diurnal surveys in rice field areas: 5-10 birds/km² in Camargue (Tourenq et al. 2001a), 5–10 birds/km^2 in the MAV (Twedt and Nelms 1999), 30 birds/km² in Japan (Fujioka et al. 2010), and the high 730 birds/km² in California (Elphick and Oring 2003). Our recorded nocturnal densities are also much greater than the mean 500 birds/km² (max 1500 birds/km²) reported in historical nocturnal surveys in the Camargue (Pirot 1982, Mesléard et al. 1995). This apparent increase in wintering bird nocturnal density is consistent with the increased importance of rice and rice weed seeds in the diets of Camargue Eurasian Teal and mallard compared to that in the 1960s and 1970s (Brochet et al. 2012). Because the majority of the 7–12 % of Camargue rice fields that are flooded are done so for hunting purposes (Pernollet et al. 2015), it is possible that limited flooded area (ca. 1000 ha) and habitat management practices dedicated to ameliorating duck numbers are responsible for the high concentrations we observed during nocturnal surveys.

Wintering ducks arrive in Camargue gradually, with maximum numbers occurring in January and diminishing when the spring migration begins in February (Tamisier and Dehorter 1999). Over this same period of time we found that seed availability decreased by 89% and 69% from early to late winter for rice and weeds, respectively. Each of these two seed types alone were still above the 50 kg/ha duck Giving-Up Density (GUD, Reinecke et al. 1989, Geer et al. 2009) at the end of the winter, so plenty of food was still available when the ducks left.
Several studies in California and the MAV showed that depletion of rice seed during winter ranged from 66–79%, and that waterfowl consumed up to 30% of the rice available during early winter (Manley et al. 2004, Eadie et al. 2008). Decomposition, granivory and germination are the primary mechanisms of rice seed loss after harvest (respectively 58%, 14% and 8% in the MAV after Stafford 2004 in Stafford et al. 2006). According to Geer et al. (2009), depletion by waterfowl ranged between 25 % and 48% in the MAV, while seed deterioration represented slightly more than 40 %. In our area, no differences in seed depletion rates were observed between flooded and non-flooded fields, even when taking into account a correction factor for non-consumptive seed mass loss in water (experimental test explained in the Methods section, Pernollet et al. in prep.). This may mean that granivores other than ducks deplete the rice/weed seed bank in dry fields as ducks do in flooded fields. For instance, wild boar and common cranes are increasing in numbers in the area, and are known to forage heavily in dry rice fields (Blondel et al. 2013). Since lack of flooding is an excluding factor for duck use (Pernollet et al. 2015), resources on dry fields are free to be exploited by other granivorous vertebrates (e.g. passerines, Elphick 2004). Seed depletion rate

was first explained by seed density, followed by post-harvest agricultural practices, with greater reduction in seed availability occurring after plowing than after other treatments or no treatment at all. Eadie et al. (2008) also reported that U.S studies showed greater seed depletion rates in fields where initial post-harvest seed density was the greatest. This means that depletion of seeds was density-dependent, as observed by Geer et al. (2009).

According to the seed densities at the beginning of winter, the carrying capacity in Camargue is 5,373 DUDs/ha or 45 ducks/ha per day for a 120 days winter. This value is markedly higher than the 1.7 to 2.3 Anatidae and Coots per hectare estimated by Tamisier and Dehorter (1999) on 60,000 ha of Camargue natural wetlands. Based on the analysis of food availability on both rice fields and wetlands, these authors concluded that the Camargue could provide winter forage for more than 400,000 ducks and coots. This value is much lower than the 53,730,000 ducks during a whole winter season we calculated if all Camargue rice fields were to be flooded. When considering that only 9% of rice fields are actually flooded, carrying capacity decreases to 4,835,700, but remains much higher than the Tamisier and Dehorter (1999) estimate.

It is important to note that we did not include seed deterioration in our carrying capacity calculations. In the U.S., the accuracy of rice field carrying capacity estimates excluding this factor have been debated, and recent data suggest actual carrying capacities are lower than have been reported (Manley et al. 2004, Stafford et al. 2006). The MAV carrying capacity estimate of 1,800 DUDs/ha (Loesch et al. 1994) was calculated without the inclusion of seed deterioration, a value that Stafford et al. (2006) recommend be reduced to 325 DUDs/ha, which is more in accordance with the 265–686 DUDs/ha previously reported by Manley et al. (2004), who also considered seed depletion and furthermore all food types (rice and weed seeds). Though we should revise our carrying capacity estimate to include seed deterioration, 5,373 duck-use days/ha in Camargue is still very high compared to the US results, such as estimation in wild rice paddies in Minnesota (3,200 DUDs/ha in Huseby et al. 2001). Moreover, other foraging habitats are available in Camargue whose carrying capacities have not been thoroughly investigated and may influence local and regional abundances, such as marshes including some that are illegally baited during the hunting season.

MANAGEMENT IMPLICATIONS

At the scale of a field (the scale at which farmers and managers will likely act), winter flooding of rice fields is the most popular duck-friendly post-rice harvest agricultural practice worldwide because it is relatively easy to implement, can provide agronomic benefits (Bird et al. 2000, Manley et al. 2005, Anders et al. 2008, Brogi et al. 2015), and makes waste seeds accessible to waterbirds (Eadie et al. 2008), (see also review by Pernollet et al, in press).

According to Kross et al. (2006), the methods that most benefit both farmers and ducks include flooding fields and leaving standing-stubble post-harvest, incomplete burns post-harvest, and generally practices that minimize mechanical treatment. In our case, we advise landowners to refrain from winter plowing or to delay it as long as possible, as this activity greatly reduces seed forage available to birds. We also recommend conservation planners to promote winter flooding of harvested fields. Where active flooding is deemed impossible or infeasible, passive flooding, achieved by closing field water gates to retain rain water, is done with success in Portugal (Lourenço and Piersma 2009) and is another practice worth promoting. In devising management plans and financial structures, managers can look to surrounding areas where support systems are already in place, such as in regions of Spain

where farmers receive financial incentives to flood their fields from the European Commission (Agri-Environmental Schemes; Pernollet et al. 2015).

Spatial distribution of rice seed between and within fields, for example in burned and unburned rows of burned fields, may profoundly influence duck foraging efficiency, but has gone largely unstudied. More direct field research on duck foraging behaviour under various flooding and straw disposal treatments and through winter as seed stocks are depleted (e.g. Rutka 2004) would be useful to better gauge the influence of the various post-harvest practices. Such studies would also provide more precise parameters for energetic models (e.g., TRUEMET: Petrie et al. 2014, ECCs: Beatty et al. 2015), and spatially explicit individual-based behavioural models (e.g. SWAMP: Miller et al. 2014), improve the prediction of movement and use of the fields by wintering ducks, and allow testing of different scenarios of winter ricefield flooding or reduction in area cultivated under rice.

The rice industry in Camargue (France) is highly reactive to changes in the political sphere, as will likely be noted following revision of the EU Common Agricultural Policy 2015, when specific financial support to rice production has been suppressed. As a result a reduction of ca. 30% of the rice area has already been recorded in the Camargue between 2012 and 2015 and a replacement with dry crops such as wheat or vegetables is observed which can be detrimental for waterbirds (C.A. Pernollet, unpub. data). In Camargue, water to flood rice fields is pumped from the Rhône River and the associated costs are too high for flooding to be feasible without support or financial assistance. Financial support of winter flooding of rice fields through Agri-Environmental Schemes, or at least passive flooding through rainwater retention, should be promoted in Camargue and throughout the wintering range of European waterfowl (Pernollet et al. 2015) to provide ample foraging grounds where necessary (such as in the Camargue, Brochet et al. 2009).

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CHAPTER III. POTENTIAL AGRONOMIC BENEFITS OF RICEFIELD WINTER FLOODING AND DUCK USE OF FLOODED FIELDS

Experimental tests, Claire Pernollet

III.1 Background information

This third chapter deals with the ecosystem services that winter flooding and ducks foraging into flooded rice fields can bring to farmers. Considering that the main constraints on rice cultivation are straw disposal and weeds, we particularly focused on weed regulation and straw decomposition improvement (**Figure 8**). These respectively represent regulating and supporting ecosystem services that could be brought to rice farmers by flooding fields and duck use.

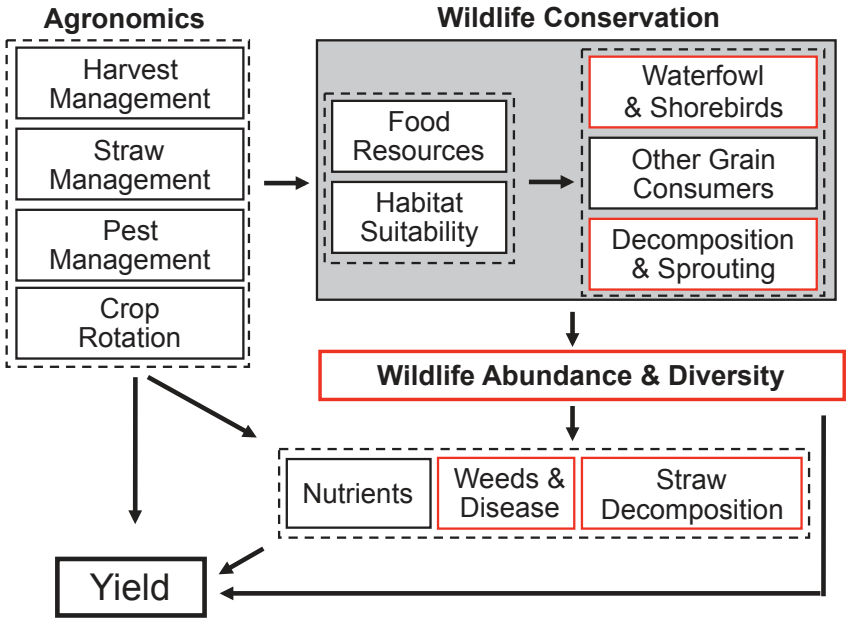

Figure 8. Integration of agronomic values and wildlife conservation in ricelands (reproduced from Eadie et al. 2008, with kind permission from S. Manley). In red colour the elements that were studied in this chapter.

Such potential agronomic benefits have been summarized by Anders et al. (2008) for the United States, then discussed in parallel to the agronomic benefits from farming ducks in the traditional Asian ‘‘Integrated Rice Duck Farming’’ (IRDF, Furuno, 2001) in **Table 2 of Article 1 (Chapter I)**. Previous empirical and experimental studies showed that ducks can bring agronomic benefits to rice farmers, but this had never been tested in Europe (except for the recently published work on nutrient recycling by waterbird in rice fields during winter by Navedo et al., 2015). We thus experimentally assessed here the effect of ricefield winter flooding on weed seed deterioration and the effects of wintering and farming ducks on weed seed banks and straw stalks.

III.2 Methods: the advantages of the experimental approach

In ecological studies, a multiplicity of factors such as site, weather or animal behaviour can affect the response variables and the precision of the measurements. The experimental approach, in which each factor is controlled for and the different parameters are precisely measured, is sometimes the best option to answer a precise question. Examples of experimental approaches for topics similar to ours include a study of buried seed samples degradation in rice fields by Fogliatto et al. (2010), or the effects of enclosed wing-clipped

mallards on straw in Bird et al. (2001). Here we used experimental tests to study seed degradation by water in greenhouse microocosms and to assess stalk trampling and seed consumption by ducks penned in a ricefield.

We assessed rice and main weed seed deterioration in dry and flooded conditions throughout the winter in a greenhouse to control for granivory by vertebrates or large invertebrates, seed quality, water and substrate heterogeneity from one field to another (**Article 4**).

We evaluated the impact of ducks on the weed seed bank and standing stalks with wing-clipped mallards in enclosures settled directly on the field to control for granivory by other vertebrates. By testing different duck densities we could also compare the potential effects of wild ducks extensively using ricelands versus high-density farmed ducks in rice-duck agroecological systems (**Article 5**).

III.3 Key messages and supporting evidence

The studies presented in the papers of this chapter provided new evidence that waterfowl-friendly management can benefit farmers through increased straw degradation, but not necessary through a reduction of the weed seed bank. These articles showed that:

1/ winter flooding increases cultivated rice and weedy rice seed mass loss, and decrease cultivated rice viability. Gross energy loss throughout the winter was greater for weedy rice in flooded fields than dry ones. No significant differences were found between dry and flooded conditions for seed mass loss, energy density or survival in barnyard grass (*Echinochloa crus-galli*) and sea clubrush (*Bolboshoenus maritimus*)(Article 4).

Besides depletion by granivorous waterfowl and other foragers, the seed bank of rice fields (rice and weeds) is reduced across the winter by seed deterioration (Geer et al., 2009). Our results showed that seeds from different species are not similarly affected by flooding, i.e. effect could be on mass loss, viability or energetic content, and differ in magnitude.

We observed seed mass to clearly decline across the winter (-38.4% on average for all species), especially so under flooded conditions, while at different rates between seed species (see also Nelms and Twedt, 1996; Foster et al., 2010; Collins et al., 2015). Cultivated rice and weedy rice lost significantly more mass across the winter under flooded than dry ricefield conditions: cultivated rice lost 46.2% of its mass under dry conditions on average, versus 62.3% if flooded; the corresponding figures in weedy rice were 26.6% and 45.3%. The magnitude of these differences was comparable to the results of Foster et al. (2010) for agricultural seeds. For the other species (barnyard grass and sea clubrush), no clear effect of flooding on seed mass loss could be detected here.

Viability of seeds generally decreased over time (-43.1% on average for all species), but the rate of such decline was greater under flooded conditions only for cultivated rice. Mean cultivated rice seed viability decreased from 99.0% at the beginning of the winter to 54.2% at the end of the season under dry conditions, versus 13.0% if flooded. For the other seed species, no clear effect of flooding on viability was detected.

In our study, we also considered seed energetic contents, with the aim to assess the value of seeds as waterfowl food. Rice farmers could be also interested in seed energetic

contents if there is a threshold below which seed loose their capacity to germinate. We observed that energy density remained relatively constant, the mean number of kJ per gram seed only increasing by 3.75% over the winter, although greater under flooded conditions. The total amount of energy available to ducks from a given seed sample hence decreased, largely owing to the loss of mass not being compensated by the slight concentration of energy. Such loss of gross energy through the winter was relatively similar between flooded and dry conditions for most seeds. The only exception was weedy rice, whose gross energy loss was 42.4% if flooded, versus only 26.2% under dry conditions.

Contrary to earlier studies, we therefore did not observe ricefield winter flooding to be a beneficial practice for farmers in terms of reduction of the seed bank viability by the end of the winter (Street and Bollich, 2003; Manley et al., 2005; Anders et al., 2008; Fogliatto et al., 2010; Baek and Chung, 2012). However, it remains to be established (in particular for weedy rice) whether seeds would sprout and seedlings would grow to a similar extent after a flooded versus dry treatment by now studying germination rates and grown weed biomass (e.g. repeat Manley et al., 2005 methodology in dry and flooded conditions). For ducks, our results suggest that the quantity but not the quality of seed food decreases across the winter.

2/ no significant effect of duck foraging was found on the seed bank, which may be explained by the patchy distribution of the seeds (Article 5).

We tested the effect of ducks foraging during a whole winter on the seed bank at three densities: 5 ducks ha^{-1} (historical nocturnal wild duck density), 23 ducks ha^{-1} (current nocturnal wild duck density), and 300 ducks ha^{-1} (Asian rice-duck farming density).

The consequence of duck foraging on the seed bank of weeds and rice leftovers was not significant. In fact, compared to the initial situation, the ducks decreased the mean number of seeds per core sample by only 3% at the highest bird density, and the seed mass by about 21% (at both the lowest and highest duck densities), which was not significant. The lack of significant effects of the ducks on the seeds may be due to the very patchy distribution of the seeds in the rice field, resulting in a highly variable number of seeds per core sample.

These results are in opposition with previous studies, which showed wintering wild ducks to significantly reduce weeds (weed biomass was reduced from 204 to 89 kg/ha in van Groenigen et al., 2003). However, despite these effects on seed density, van Groenigen et al. (2003) did not observed differences in yield between areas that were visited by waterfowl and those where waterfowl were excluded. These results suggest that either the weed densities were not sufficient to impact yield, or that farmers were in all cases adequately controlling their weeds through other management approaches. This would also suggest that the direct benefits from waterfowl activity may be confined to extremely weedy fields, situations where farmers are not depending on herbicides for weed control, such as in organic production, or when waterfowl use the fields during the rice growing period rather than the winter inter-crop season (IRDF, Furuno et al., 2001).

3/ duck trampling and foraging on straw significantly reduce the standing stalks and contribute to their immersion, which may increase straw decomposition rate further still (Article 5).

Two Californian studies previously tested the hypothesis that foraging activities of waterfowl could facilitate straw decomposition in winter (Bird et al., 2000; van Groenigen et

al., 2003). Both observed through experimental tests that the trampling of the ducks had a direct effect on the straw by flattening and cracking it, resulting in an increased contact with the soil and greater accessibility for microbial decomposers. Such waterfowl activity helped to reduce lignin and nitrogen concentrations in the surface residue, increasing rice straw decomposition, soil nitrogen availability, and straw incorporation into the soil. With high duck densities, disappearance of residual surface straw could increase by up to 76% (Bird et al., 2000). Van Groenigen et al. (2003) observed that straw biomass reduction in flooded fields with waterfowl was more than twice greater than without waterfowl.

This is the first time that stalks have been considered since previous studies concentrated on lying residual straw. We simulated with many birds in a small enclosure over a short period of time the presence of a lower density of ducks during one whole winter. This prevented us from measuring straw decomposition over several months, but only stalk submersion (as opposed to Bird et al., 2000). The tests however showed that ducks reduced the stalks significantly, and that reduction increased with duck density: -27 % for 5 ducks ha^{-1} over a whole winter, -52 % for 23 ducks ha^{-1}, and -91 % for 300 ducks ha^{-1}, the Asian rice-duck farming density.

The results of these three studies demonstrate that rice farmers can expect winter-flooding to promote straw decomposition but likely not a reduction of the weed seed bank by the end of the season. They also show that the expected benefits in terms of straw disposal can be enhanced further by the presence of foraging waterfowl.

Article 4:

Effect of winter flooding on deterioration of rice and main rice weed seeds: a greenhouse experiment

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ABSTRACT

Leftover seeds after ricefield harvest are simultaneously viewed as troublesome weeds by rice growers and as a potentially valuable source of food by waterfowl during winter. One management that have been though to participate to weed seed control as well as providing access to energetic food to waterfowl is ricefield winter flooding. Besides consumption by a range of foragers, the extent to which flooding will deteriorate the seeds, and in particular affect their energy density, remained an open question so far. Seed deterioration rate of three main rice weeds (*Oryza sativa* var., *Echinochloa crus-galli* and *Bolboshoenus maritimus*) and cultivated rice was experimentally investigated in flooded and non-flooded ricefield conditions across the winter 2014-2015 in Camargue, France. Seed mass loss, energetic content density and seed viability were monitored during early (post-harvest), mid- and late winter. In general seed mass and viability declined across the winter (-38.4% and -43.1% on average for all species, respectively), while energy density (kJ/g) increased slightly (+3.75% on average for all species). Seeds from different species were not similarly affected by flooding, i.e. the effects differed in magnitude. Cultivated rice and weedy rice lost significantly more mass across the winter under flooded than dry ricefield conditions: cultivated rice lost 46.2% of its mass under dry conditions on average, versus 62.3% if flooded; the corresponding figures in weedy rice were 26.6% and 45.3%. The rate of viability loss was greater under flooded conditions only for cultivated rice (99.0% at the beginning of the winter, 54.2% at the end of the season under dry conditions, versus 13.0% if flooded). The total amount of energy available to ducks from a given seed sample hence decreased, largely owing to the loss of mass not being compensated by the slight concentration of energy. Such loss of gross energy through the winter was relatively similar between flooded and dry conditions for most seeds. The only exception was weedy rice, whose gross energy loss was 42.4% if flooded, versus only 26.2% under dry conditions. For farmers, it remains to be established (in particular for weedy rice) whether seeds would sprout and seedlings would grow to a similar extent after a flooded versus dry treatment. For ducks, our results suggest that the quantity but not the quality of seed food decreases across the winter.

INTRODUCTION

During winter, leftover seeds on the soil surface of rice fields are viewed as potentially troublesome weeds or rice yield loss by agronomists and farmers, while they are considered as a potentially valuable source of food for wintering wildlife by conservation practitioners (Rodenburg & Johnson, 2009, Stafford *et al*., 2010, respectively). The points of view of both groups of stakeholders are not necessarily mutually exclusive, since granivorous birds such as waterfowl can contribute to weed control (e.g. Smith & Sullivan, 1980; Van Groenigen *et al*., 2003) and some waterfowl-friendly management of the fields may also induce greater weed degradation (e.g. Street & Bollich, 2003, Manley *et al*., 2005).

Among such waterfowl-friendly post-harvest agricultural practices in rice fields, winter flooding is the most popular because it is relatively easy to implement, can readily provide significant agronomic benefits (Anders *et al*., 2008; Brogi *et al*., 2015), and makes waste seeds accessible to waterbirds (Eadie *et al*., 2008). This winter management practice is mainly applied in the U.S (Eadie *et al*., 2008) and in some regions of Japan (Fujioka *et al*., 2010), and to a much lesser extent in Europe (Pernollet et al., 2015a). In fact, most rice fields worldwide are kept dry during the post-harvest period. Besides the fact that dry conditions prevent most waterfowl foraging (Guillemain *et al*., 1999), the consequences of dry vs. flooded management for seed deterioration across the winter have been little studied (except for Foster *et al.*, 2010; Fogliatto, Vidotto & Ferrero, 2010; Baek & Chung, 2012). Some similar comparative studies are available on seed dormancy break and germination (Baskin, Baskin & Chester, 2003).

Previous studies have reported that rice seeds are more resistant to decomposition under flooded conditions than some weed seeds and have higher nutritional values than other seed crops, hence being an important source of potential food to wintering birds (Nelms & Twedt, 1996; Kaminski *et al.*, 2003). However, the rate of seed deterioration into water has been shown to differ between plant species (Nelms & Twedt 1996), some plants actually being favoured (Maria del Mar Catala com. pers.) or highly resistant (Mesléard *et al*., 1999), while others could be greatly reduced. For example, winter flooding has been reported as an efficient technique to reduce weedy red rice *Oryza sativa* var. (Fogliatto, Vidotto & Ferrero, 2010; Baek & Chung, 2012).

Published over-winter depletion rates of rice seeds in the U.S. ranged from 66 to 79% (Manley *et al.,* 2004; Eadie *et al*., 2008), while a 89% and a 69% mass decrease have been recorded for rice and weeds in France, respectively (Pernollet *et al*., unpublished data). Decomposition, granivory and germination are the primary mechanisms of seed loss after harvest (respectively for rice: 58%, 14% and 8% in the Mississippi Alluvial Valley [MAV] after Stafford (2004), slightly more than 40% for rice deterioration according to Geer *et al.,* 2009). Decomposition is usually defined as seed mass loss (Nelms & Twedt, 1996; Foster *et al.*, 2010; Collins *et al.*, 2015), sometimes for specific weeds as decreased seed viability or germination capacity (Fogliatto, Vidotto & Ferrero, 2010; Baek & Chung, 2012), or as a reduction of weed plant biomass in spring (Manley *et al*., 2005). The potential decrease in seed energetic content is an important element to take into account when considering seed decomposition. Energetic content is obviously also of paramount importance to foraging animals, such that one of the criticisms made by Elphick *et al*. (2010) at the end of their literature review on rice farming and waterbirds was that scientists generally ignore the amount of energy and the nutrition value provided by these seeds for waterbirds (Checkett *et al*., 2002; Kaminski *et al*., 2003), and how that value might change throughout the winter

(Nelms & Twedt, 1996). On the other hand, rice farmers may seem less interested in seed energetic content. However, the ability of plants to germinate and grow is clearly linked to the available energy in the seed that will be used the first days by the seedling (Come, 1970), so whether or not a given winter practice may reduce weed seed viability is likely the most important issue to them. The simultaneous consideration of seed mass, seed energetic content and seed variability should help agronomists and ecologists to better understand the mechanisms of seed deterioration across the winter, and provide shared currencies for these stakeholders to evaluate the potential benefits brought by winter flooding of the rice fields.

This study undertook an evaluation of the effects of post-harvest ricefield flooding on changes in these three determinant variables across an entire winter for cultivated rice as well as three main weed seeds (*Oryza sativa* var., *Echinochloa crus-galli* and *Bolboshoenus maritimus*) which rice growers have to face. The test was conducted under laboratory conditions to focus on the effects of seed deterioration, discarding the potential effect of depletion by granivorous vertebrates and potentially also some invertebrates. An experimental approach was selected so as to isolate the deterioration processes at play while avoiding potential confounding effects from field conditions and to test whether winter flooding, 1) led to differential seed deterioration rates across the winter in terms of seed mass loss, changes in energetic content and seed viability, and how these variables were related to each other, 2) affected some seed species more than others, in particular rice versus weed seeds, and 3) determine what these results imply for rice growers and waterfowl conservation planners.

Methods

Study area, species, treatments and response variables

The experiment was conducted during the winter 2014-2015 in microcosms consisting of plastic trays positioned in a greenhouse (without temperature regulation) at the Tour du Valat Research Center situated in the delta of the Rhône River, Camargue, Southern France (43°30'N, 04°40'E). This delta, one of the only regions in France where rice is grown (around 15 000 ha of rice fields embedded into a 60 000 ha wetlands complex), constitutes the most important winter quarter for ducks in the country, and one of the most important at the European scale for these duck species (Tamisier & Dehorter, 1999; Critical Site Network Tool, 2015).

We assessed seed deterioration of cultivated rice (*Oryza sativa L.*, common round bred cultivar "Gageron") and three rice weeds, i.e. two Poaceae (weedy rice *Oryza sativa* and barnyardgrass *Echinochloa crus-galli*) and one Cyperaceae (sea clubrush *Bolboshoenus maritimus*). These species were selected because they constitute the main rice weeds in the Camargue as well as in Europe (Marnotte *et al*., 2006), and because of their high occurrence in studies of migrating and wintering ducks' diet (Brochet *et al*., 2010), i.e. they are important food to waterfowl.

At the end of October 2014, samples of soil and fresh mature seeds were hand collected just before rice harvesting time from twelve different rice fields cultivated in the conventional way (i.e. non-organic) from three different farms. All collected soil samples were mixed with each other before the experiments. The mature seeds were directly picked from the plants, and dried at 30°C to constant mass. The seeds from each species were then placed into labelled fine mesh polyester bags (mesh <0.05 mm) securely closed with staples in order to avoid contamination of the samples with seeds potentially present in the ricefield substrate, whilst at

the same time still allowing chemical, gas and microbial exchanges with the substrate. Three sets of two grams of fresh seeds (from only one seed species at a time) were weighed to the nearest 0.1 mg and put in each bag. A first set of seed samples was prepared at the beginning of the tests but did not receive any treatment, and was considered as our initial starting point: "Time 1" (early winter, mid-October). The samples for Time 1 were as numerous as the samples for the other two times. The two other sets of seed samples received special treatments (described below) and were sampled (i.e. taken back from the microcosms) at two different periods during the winter ("Time 2" and "Time 3" described below). A total of 216 samples of 2 grams of each seed species were thus used (4 species x 3 treatments x 3 measurement periods x 6 replicates).

There were on average 79.8 ± 0.9 seeds of cultivated rice, 89.0 ± 2.0 seeds of weedy rice, 687.6 ± 0.2 seeds of barnyardgrass and 1156.3 ± 0.4 seeds of sea clubrush. Seeds of cultivated rice and weedy rice were counted in each sample, while the number of seeds per sample of the two other (much smaller) seed species were estimated by weighting 20 seeds 20 times, hence the difference in relative error compared to mean number of seeds above.

Three different environmental treatments were applied to the seed samples, contained in microcosms of 18 plastic trays (10 cm high and 8 liters volume), i.e. 3 treatments x 6 replicates = 18 trays per species and time period:

(1) "NON-FLOODED": the seed bags were buried within the upper 5 cm of the substrate, which was kept dry throughout the winter.

(2) "FLOODED": the seed bags were buried within the upper 5 cm of the substrate, which was flooded under 7 cm of water from the rice field irrigation network.

(3) "CONTROL": the seeds bags were left in water without ricefield substrate. This last treatment was identified as the control because it allowed us to assess if seed deterioration was due to water itself and/or the additive effect of the substrate and the microorganisms present in it.

Seed samples were progressively recovered from the trays and analysed at three times during the duck wintering time (between September and March), "Time 1" is hereafter referred to as T1 (prior to any treatment, early winter, 20th October), "Time 2" as T2 (mid-winter, 17th December, i.e. after 58 days of treatment) and "Time 3" as T3 (late winter, 20th February, i.e. after 123 days of treatment). The later period is comparable to the longest length of time that the rice fields in the area are submerged if they get flooded (October to mid-February; Pernollet *et al*., 2015).

At each time period three response variables were measured: remaining seed mass from the initial 2 grams (g), seed energetic content (kJ/g), and seed viability rate (ratio of live embryos to total live+dead ones).

Measurements

Prior to measurements of the seed samples at Times 2 and 3, the samples were lightly washed through a 300 μm sieve to remove silt and clay particles.

Seed viability

We used five randomly chosen seeds from each sample to estimate embryo viability using the standard tetrazolium method (De Vlaming & Proctor, 1968). Seeds were cut to expose embryos and put on a filter paper saturated with 1% tetrazolium solution in a Petri dish, then placed in the dark at room temperature for 24h. Seeds with a positive tetrazolium response (i.e. embryos were respiring and turning pink) were assumed to be viable (Nachlas *et al*., 1960). Note that for cultivated and weedy rice, whose seeds are relatively heavy, five additional seeds were added to the initial 2 grams in each sample, in prevision for these viability tests. The seeds used for testing viability in these species were therefore not included in the weight measurement.

Remaining seed mass

Each sample was dried over several days at 30°C to constant mass, then weighed to the nearest 0.1 mg.

Seed energetic density

All samples were then placed into a Petri dish and sent to the CNRS Strasbourg university laboratory (Northern France). Each seed sample was freeze-dried (Lyophilizer Christ Alpha 1-4) to constant mass and ground to a fine homogeneous powder using a grinder (Retsch ZM1). Energy content was determined on c.a. 0.4 – 1.4 g dry aliquots, weighed to the nearest 0.1 mg, using a calorimeter (Parr Instrument 6200) standardized with benzoic acid. We checked that there was a linear relationship between the mass of the samples and their energy content over this range of masses (r^2=0,999, $p<0.001$, n= 20). For 57 % of the samples (depending on the total amount of powder available per sample) measurements were performed in duplicate (measurement reproducibility between duplicates = 0.6± 0.2%). We obtained energetic content per gram of dry mass, i.e. energetic density (KJ/g) for all 6 replicates of each seed sample for each treatment and each of the 3 time periods.

Statistical analyses

In order to test for potential differences among plant species in terms of seed mass loss over time and depending on treatment, we used the remaining mass of seeds (from the initial 2g) measured at Time 2 and Time 3, and ran a set of generalized linear mixed models (GLMM) with a Gaussian error structure including plant species, treatment (non-flooded, flooded, control), their interaction, and date to compare short vs. long floods/drought (Oct-Dec vs Oct-Feb) as fixed factors, and considered replicate (i.e., tray) ID as a random factor to take into account the pseudo-replication induced by the fact that some seed samples were in the same plastic tray.

For the energetic density of seeds, we first compared the mean species-specific values at the beginning of the experiment (T1). As significant differences were detected between plants (cf. results), we then considered the energetic density loss or gain ratio, i.e. differences between energetic densities in T2 or T3 and the average value in T1, divided by the average value in T1. GLMMs with the same fixed and random factors as above were then used.

For seed viability, each tested seed was attributed the value 0 when dead or 1 when alive. As above, we first compared mean viability rates between species at the beginning of the experiment (T1). We then ran GLMMs with viability data in December (T2) and February

(T3) considered with a binomial error structure, including the same fixed and random factors as above.

For mass analyses and energetic density of seeds, normal distribution of the residuals was tested prior to further analyses (Shapiro Wilk test) and no transformation was necessary.

For each of the three response variables, all plausible models were ranked and the best models were selected using the Akaike Information Criterion (AIC) considering all models with $\Delta AIC < 2$ from the best model as equally good at fitting the data. The relative performance of the models was assessed by their AIC weight (Burnham & Anderson, 2002). Overall significance of fixed variables was tested by analysis of deviance. When a significant effect was detected (deviance test, $P < 0.05$), we performed pair-wise comparisons of means using Tukey's post-hoc test to assess whether the differences between the components of the variables were significant or not for the target modelled variables (procedure details in Burnham & Anderson, 2002).

Unless otherwise stated, all information presented in the text and in the graphs refer to predicted values extracted from the best models. Means are given with their 95 % confidence intervals or range. All analyses were conducted using R version 3.1.3 (R Core Team, 2013), with libraries 'lme4' (Bates *et al*., 2014), 'nlme' (Pinheiro *et al*., 2015) 'AICcmodavg' (Mazerolle, 2015) and 'multcomp' (Hothorn *et al*., 2008).

RESULTS

Remaining seed mass

The best model for explaining remaining seed mass across the winter was the full model including all tested variables, i.e, species, treatment, their interaction and the time period (GLMM, $X^3_{15}= 222.66$, $P < 0.001$, Table 1). This model accumulated 99% of AIC weight and all included variables were significant at $P < 0.001$. Mean remaining seed mass differed between seed species ($F_{3,116} = 59.07$, $P < 0.001$), with sea clubrush samples retaining a greater mass over time than cultivated rice ($z = 5.31$, $P < 0.001$), barnyardgrass ($z = 3.72$, $P = 0.001$) and weedy rice ($z = 3.09$, $P = 0.01$) (the other pairwise differences between species being non-significant). Non-flooded, flooded and the water control treatment had a different influence on remaining seed mass ($F_{2,15} = 17.78$, $P < 0.001$), with greater average remaining mass in non-flooded than flooded ($z = -5.43$, $P < 0.001$) and non-flooded vs. control (water alone: $z = 3.22$, $P = 0.004$) conditions. Flooded conditions with only water (i.e. control) did not induce different average remaining seed mass than the proper flooded treatment with ricefield substrate ($z = -2.21$, $P = 0.07$) (Fig. 1). The period effect was significant ($F_{1,116}= 245.91$, $P < 0.001$), with lower remaining seed mass at T3 than T2, i.e. longer treatments having a greater effect on remaining seed mass ($z = -15.68$, $P <0.001$). Considering the effect of the species-treatment interaction and discarding the control treatment, we found seed mass lower in flooded than non-flooded conditions for cultivated rice and weedy rice (respectively: $z = -4.67$, $P < 0.01$; $z = -5.43$, $P <0.01$). The treatment effect was not statistically significant for barnyardgrass and sea clubrush seeds (respectively: $z = -1.57$, $P = 0.92$; $z = -0.51$, $P = 1.00$).

Across the winter, model estimates suggest cultivated rice lost 46.2% [41.3–51.2] of its mass under dry conditions on average, versus 62.3% [57.4–67.3] if flooded; weedy rice lost 26.6% [21.6–31.5] of its mass under dry condition versus 45.3% [40.4–50.3] if flooded. Regardless

of treatment, barnyardgrass and sea clubrush seeds lost an average of 40.6% [35.7–45.6] and 24.4% [19.4–29.3] of their mass across the winter, respectively (Fig. 1).

Table 1 Model selection to evaluate the influence of the species (rice, weedy rice, barnyardgrass, sea clubrush), treatment (non-flooded, flooded, control), period (T2, T3) and species*treatment on seed mass across the winter 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and model weight (wi) are provided for plausible model sets involving the main effects and key interaction. Random factor: replicate (i.e. tray) ID.

Model	K	AIC	ΔAIC	w_i
Species + Treatment + Period + Species x Treatment	10	-88.51	0	0.999
Species + Treatment + Period	9	-73.80	14.72	0.001
Species + Period	6	-56.30	32.21	1.01E-07
Treatment + Period	5	27.90	116.41	5.27E-26
Period	2	39.29	127.80	1.77E-28
Species + Treatment	7	58.64	147.16	1.11E-32
Species + Treatment + Species x Treatment	8	60.72	149.24	3.92E-33
Species	4	67.78	156.29	1.15E-34
Treatment	3	104.89	193.40	1.01E-42

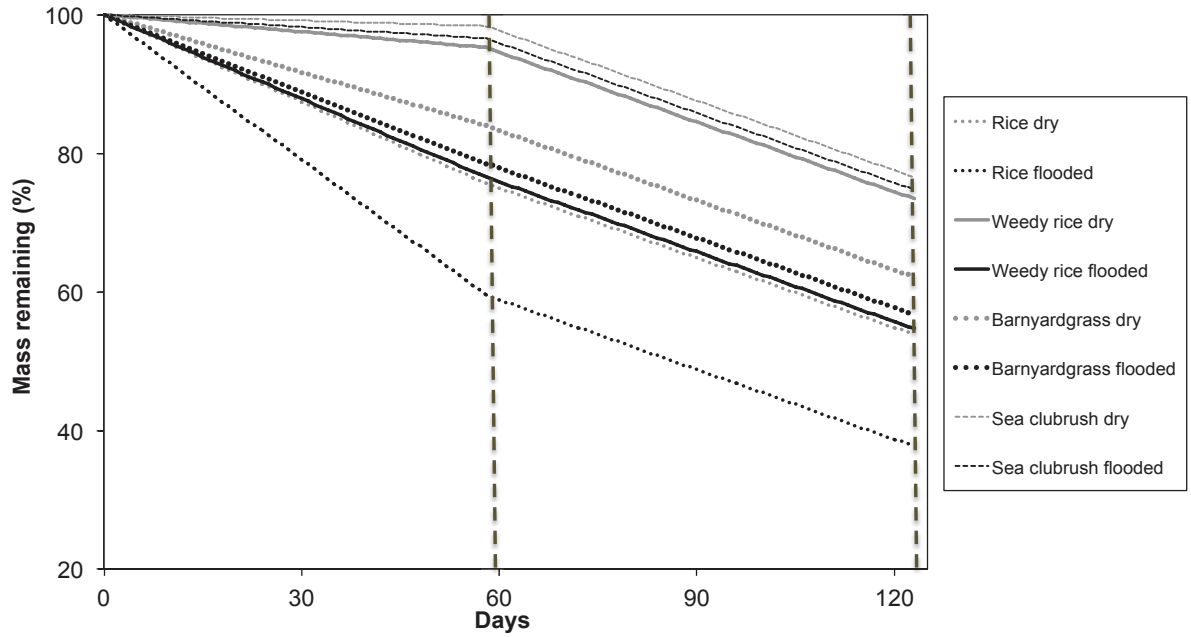

Fig. 1 Predicted percentages of mass remaining for seeds of cultivated rice and three main rice weeds (weedy rice, barnyardgrass, sea clubrush) computed from estimated remaining seed mass by the best selected model (cf. Table 1), after being left in dry ricefield substrate or submerged in flooded ricefield substrate during the winter of 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Samples (2g of seeds initially) were weighted at day 58 (T2) and day 123 (T3, vertical lines). The effects of the control treatment (water only, with no substrate in trays) did not significantly differ from flooded (see text) and are therefore not represented.

Seed energetic density

Mean energetic density differed among seed species at the beginning of the experiment ($F_{3,68}$ = 275.8, $P < 0.001$, Adjusted R^2: 0.92). From the richest to the poorest, we found sea clubrush (19.7 kJ/g [19.5–19.9]) > barnyardgrass (18.3 kJ/g [18.2–18.4]) > weedy rice (16.9 kJ/g [16.8–17.0]) > cultivated rice (16.5 kJ/g [16.3–16.8]).

The best model for explaining change of seed energetic density across the winter was the same as for remaining seed mass, i.e. the full model including all tested variables: species, treatment, their interaction and period (GLMM, X^3_{15} = 114.2, $P < 0.001$, Table 2). This model accumulated 92% of AIC weight; all single variables were significant at $P < 0.001$ and the species-treatment interaction at $P = 0.016$. Energetic density of seed increased across the winter (Period: $F_{1,115}$ = 39.41, $P < 0.0001$), with a greater effect from T1 to T2 than from T1 to T3 ($z = 6.24$, $P < 0.0001$). Non-flooded, flooded and the water control treatment had a different influence on changes in seed energetic density ($F_{2,15}$ = 61.43, $P < 0.001$), with a lower positive effect in non-flooded than flooded ($z = 6.31$, $P < 0.0001$) or non-flooded than control (water alone: $z = -5.23$, $P = 0.004$) treatments, while the effects of control and flooded conditions did not differ ($z = 1.08$, $P = 0.53$) (Fig. 2). Considering the species-treatment interaction, and discarding the control treatment, we found flooded conditions induced a greater increase in seed energetic density than dry conditions for all species, except for sea clubrush where no significant treatment effect was detected ($z = 2.21$, $P = 0.54$).

Across the winter, all seed species concentrated energy under all treatments, but estimates from the best model suggested cultivated rice concentrated 4% more energy per gram on average when flooded compared to non-flooded, with similar effects of flooding compared to non-flooding being 4.5% for weedy rice, and 4% for barnyardgrass (Fig. 2).

Table 2 Model selection to evaluate the influence of species (rice, weedy rice, barnyardgrass, cosmopolitan bulrush), treatment (non-flooded, flooded, control), species*treatment and period (T2, T3) on energetic density change (difference between energetic density at T2 or T3 and the average value at T1, divided by the average value in T1). Numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and model weight (wi) are provided for plausible model sets involving main effects and the key interaction. Random factor: replicate (i.e. tray) ID.

Model	K	AIC	ΔAIC	w_i
Species + Treatment + Period + Species x Treatment	10	-712.83	0	0.92
Species + Treatment + Period	9	-707.84	4.99	0.08
Treatment + Period	5	-681.15	31.68	1.22E-07
Species + Treatment + Species x Treatment	8	-677.42	35.41	1.89E-08
Species + Treatment	7	-676.16	36.68	1.00E-08
Species + Period	6	-671.42	41.41	9.39E-10
Treatment	3	-656.30	56.53	4.89E-13
Period	2	-645.98	66.85	2.81E-15
Species	4	-641.10	71.74	2.44E-16

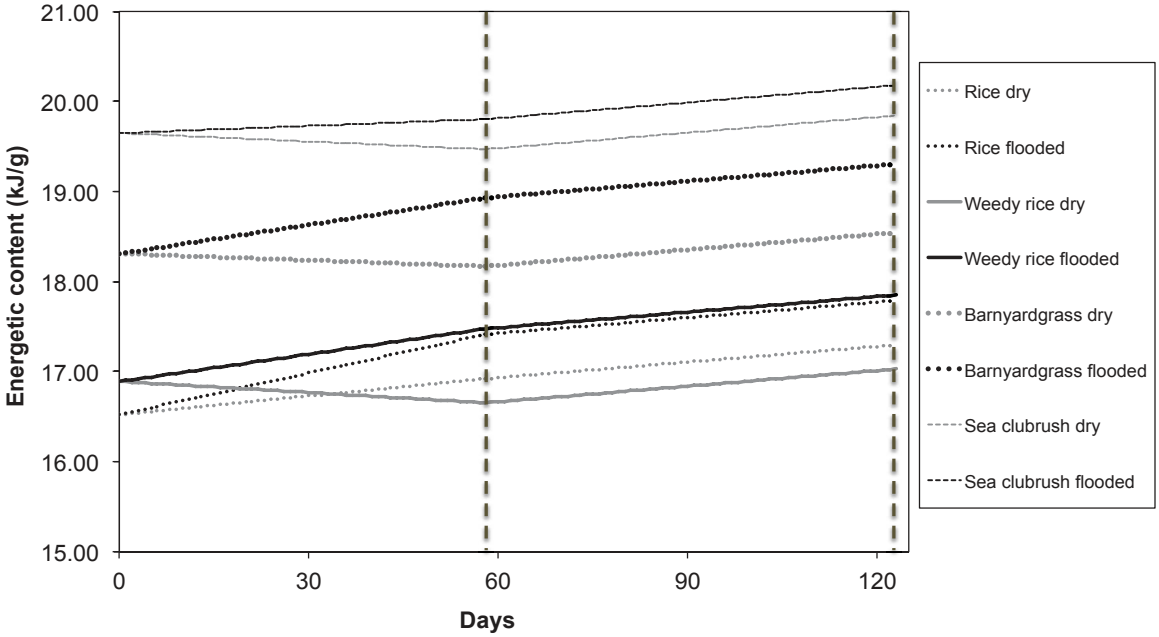

Fig. 2 Predicted energetic density per gram of seeds of cultivated rice and three main rice weeds (weedy rice, barnyardgrass, sea clubrush) computed from estimated energy density change from the best selected model (cf. Table 2). Values from samples kept in dry ricefield substrate or submerged in flooded ricefield substrate during the winter 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Samples at time T2 and T3 were extracted from the experiment at day 58 and day 123 (vertical lines). The effects of the control treatment (water only, with no substrate in trays) did not significantly differ from flooded (see text) and are therefore not represented.

Seed viability

Seed viability differed among plant species at the beginning of the experiment ($F_{3,30}$= 4.90, P < 0.007, Adjusted R^2: 0.26). This viability was significantly higher for cultivated and weedy rice than for sea clubrush (t = -3.68, P = 0.005 and t = -2.98, P = 0.03, respectively) while the other comparisons yielded non-significant results. From the greatest to the lowest initial seed viability we found cultivated rice (99.0% [96.9–100]) > weedy rice (96.9% [93.0–100]) > barnyardgrass (93.3 [89.6–97.1]) > sea clubrush (88.9% [84.5–93.2]).

The best model for explaining viability of seeds across the winter was, as above, the full model including all the tested variables i.e, species, treatment, their interaction and period (GLMM, X^2_{14} = 79.92, P < 0.001, Table 3). This model accumulated 99% of AIC weight; period and the species-treatment interaction had a significant effect at P < 0.001, species and treatment were significant at P = 0.001 and P = 0.002, respectively. Viability of seeds decreased across the winter (T2 compared to T3, z = -4.00, P < 0.0001). Average seed viability was greater in non-flooded conditions than in the water-only control (z = 2.86, P = 0.01) but was not different from the flooded treatment (z = -2.05, P = 0.10), which itself did not differ from the water-only control (z = 0.87, P = 0.66). Considering the species-treatment interaction, and disregarding the control treatment, cultivated rice was the only species with lower seed viability in flooded than in non-flooded conditions (z = -4.50, P < 0.01) (Fig. 3).
Across the winter, mean cultivated rice seed viability decreased from 99.0% [96.9–100] at T1 to a mean of 54.2% [39.2–68.4] at T3 under dry conditions, versus 13.0% [6.7–23.9] at T3 if flooded. Weedy rice seed viability changed from 96.93% [92.98–100] at T1 to a mean of 66.7% [51.6–78.9] in dry and flooded condition at T3. Barnyardgrass seed viability decreased

from 93.3% [89.6–97.1] at T1 to a mean of 60.9% [45.7–74.2] in dry and flooded condition at T3. Finally, sea clubrush seed viability changed from 88.9% [84.5–93.2] at T1 to a mean of 57.0% [41.8–71.0] in dry and flooded condition at T3 (Fig. 3).

Table 3 Model selection to evaluate the influence of species (rice, weedy rice, barnyardgrass, sea clubrush), treatment (non flooded, flooded, control), period (T2, T3) and species*treatment on seed viability across the winter 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Numbers of parameters (K), Akaike's Information Criterion (AIC), difference from lowest AIC value (Δ AIC), and model weight (wi) are provided for plausible model sets involving main effects and the key interaction. Random factor: replicate (i.e. tray) ID.

Model	K	AIC	ΔAIC	w_i
Species + Treatment + Period + Species x Treatment	10	910.30	0.00	0.999
Species + Treatment + Species x Treatment	8	924.63	14.34	7.71E-04
Species + Treatment + Period	9	930.68	20.38	3.75E-05
Species + Period	6	937.51	27.21	1.23E-06
Species + Treatment	7	944.24	33.95	4.25E-08
Treatment + Period	5	946.29	35.99	1.53E-08
Species	4	951.08	40.79	1.39E-09
Period	2	953.12	42.83	5.01E-10
Treatment	3	959.37	49.08	2.20E-11

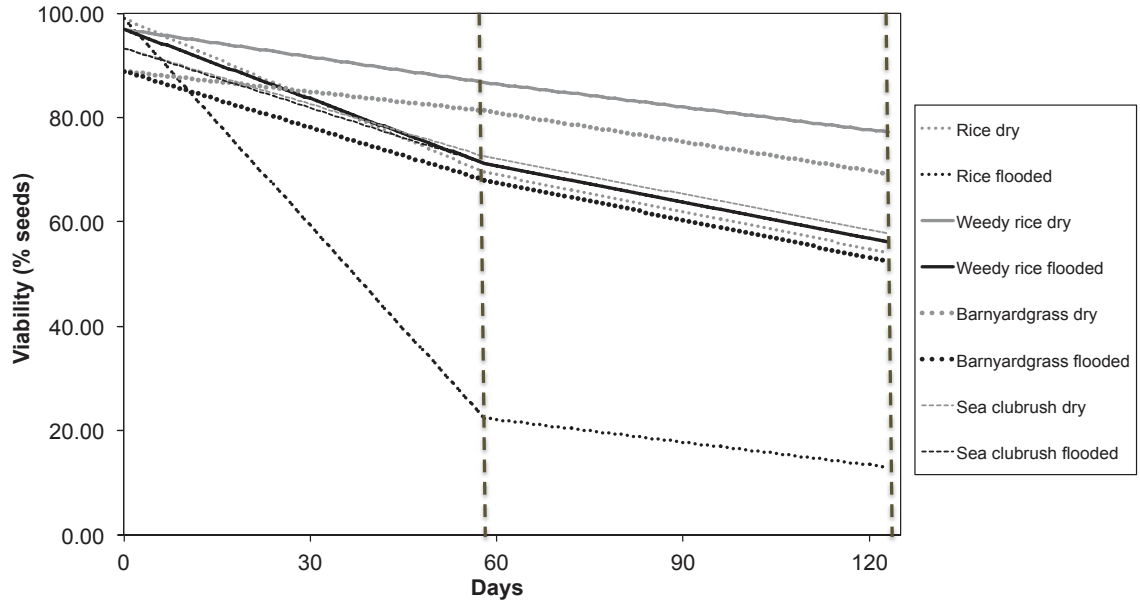

Fig. 3 Predicted viability (%) for seeds of cultivated rice and the three main rice weeds (weedy rice, barnyardgrass, sea clubrush) computed from estimates from the best selected model (cf. Table 3), after being left in dry ricefield substrate or submerged in flooded ricefield substrate during the winter 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Viability of seeds was estimated at T2 (58 days) and T3 (123 days)(vertical lines). The control treatment (water only, with no substrate in trays) did not significantly differ from flooded (see text) and is therefore not represented.

DISCUSSION

The fate of rice leftovers and weed seeds across the intercrop season is important to farmers and conservationists alike: for the former, reducing the weed seed bank may be a major issue since encroachment by undesired plants is a major limiting factor of rice cultivation worldwide (Baki *et al.*, 2000; Oerke, 2006; Marnotte *et al*., 2006; Anders *et al.*, 2008; Rodenburg & Johnson, 2009). For the latter, who view harvested rice fields as a potential foraging habitat for wildlife, seed abundance across the winter may determine field attractiveness and overall habitat carrying capacity (e.g. Manley *et al.* 2004, Stafford *et al.* 2006,). Despite the fact that the objectives of these two categories of stakeholders are different, some agricultural practices, especially the winter flooding of the harvested fields, have been recognised as mutually beneficial since they allow reduction of weed abundance while making the seeds available to foraging waterfowl (Eadie *et al.*, 2008 versus Anders *et al.*, 2008).

Besides depletion by granivorous waterfowl and other vertebrate and invertebrate foragers, the seed bank of rice fields is decreased across the winter by seed deterioration (Geer *et al*., 2009). Agronomists have mostly considered such deterioration through the proportion of viable seeds at the end of the winter, as this will determine weed infestation of the next crop (Baek & Chung, 2012). Ecologists and wildlife managers have rather been interested in the mass of seeds available to foraging animals (Nelms & Twedt, 1996; Foster *et al.,* 2010; Collins *et al.*, 2015). With a few exceptions (studies on seed dormancy break and germination: Fogliatto, Vidotto & Ferrero, 2010; Baek & Chung, 2012), seed deterioration has in both cases mostly been evaluated through field experiments (on weedy rice from ecologists and agronomists, respectively: Manley *et al.*, 2005 and Fogliatto, Vidotto & Ferrero, 2010). Albeit very conclusive in most cases, and often showing a positive effect of winter flooding on seed deterioration rates, such field studies do not easily allow assessing the mechanism by which the seed bank is reduced (e.g. loss of seed components, death of the seeds, depletion by invertebrates, etc). By isolating factors in microcosms in a greenhouse experiment, this experiment allowed us to assess more precisely some of the mechanisms by which seed deteriorate across the winter, and the effect of flooding without any consumption by vertebrates and large invertebrates. In particular this experiment allowed us to study the importance of seed energetic contents on the deterioration process, which had not so far been analysed. The measurement of mass and energy help us to have a clear idea of what may provide the flooding of rice fields to birds during the wintering season (Miller & Eadie, 2006 on waterfowl energetic requirements).

As expected, we observed seed mass to clearly decline across the winter, especially so under flooded conditions, and at different rates between seed species (Nelms & Twedt, 1996; Foster *et al.,* 2010; Collins *et al.*, 2015). Energy density remained relatively constant, since the average 3.75% increase in kJ/g was statistically significant, but likely biologically insignificant. Viability of seeds generally decreased over time (-43.1% on average for all species), but the rate of such decline was greater under flooded conditions only for cultivated rice.

Seeds lost 38.4% of their initial mass on average. Flooding led to cultivated and weedy rice seeds to loose 1.35 and 1.70 times more mass than under dry conditions, respectively, which is comparable to the 1.4-3.3 times increase recorded by Foster *et al*. (2010) for agricultural seeds under flooded versus dry conditions. These authors hypothesized that the differences in rates of loss between seed species could be due to easier microbe colonization after

differential softening, dwelling and deterioration of seed coat by water. The similarity in seed mass deterioration between the water-only and the water+sediment treatments in our experiments, suggests a major role of water and water microorganisms *per se* than the soil chemicals and microbial activity. Following on to Foster et al.'s (2010) hypotheses, the cultivated and weedy rice seed coat, in particular, may have been particularly deteriorated by water in our study. Our mean rice seed mass loss under flooded conditions (62.3%) was somewhat greater than the value obtained by Geer et al. (2009) in field experiments (44 to 47%) or the results of Nelms & Twedt (1996), i.e. 20% rice seed mass loss, which led these authors to conclude that rice seeds were particularly resistant to deterioration in water than most grains and natural foods. It is possible that the experimental conditions in trays (e.g. different temperature regimes) led to a greater rice mass loss than what would have been observed if the seeds had remained in the sediment of a proper field. However, under similar conditions the mass of the different seed species tested decreased at different rates, and not all seeds were similarly affected by flooding.

Earlier studies considered that seed mass loss and nutrient loss were likely correlated for most plant species (McGinn & Glasgow, 1965). However, some authors conversely hypothesized that seed deterioration through mass loss to winter flooding may actually reduce the value of seeds to foraging waterfowl by the end of the winter (Naylor et al., unpublished). Our results clearly showed that energy density was not gradually lost through the winter but rather slightly increased, especially under flooded conditions, although to a very moderate extent (3.75%). We can hypothesize that some of the energy reserves initially present in the seeds possibly became slightly concentrated in the developing embryo during the winter, but the main result is therefore that the intrinsic quality of the seed material remained globally constant throughout the winter, regardless of flooded/dry conditions.

From the point of view of waterfowl, the slight gradual concentration of energy in the seeds did not compensate for the general loss of seed mass, so that the total energy available (expressed in kJ rather than kJ/g seeds) markedly declined over the winter (range -22.3 to -62.3%, Table 4). The gross energy loss through the winter was relatively similar between flooded and dry conditions for most seeds. The only exception was weedy rice, whose gross energy loss (for one initial gram of seeds) was 42.4% if flooded, versus only 26.2% under dry conditions. As opposed to earlier studies suggesting that cultivated rice would represent a better forage to waterfowl than weeds (Kaminski *et al.,* 2003), our results conversely suggest that, for a similar initial mass of seeds, cultivated rice was the poorest food resource and sea clubrush the richest, the difference between these seed species gradually increasing across the winter in both flooded and dry conditions (Table 4).

Table 4 Energy loss across the season for 4 seed species under a flooded or dry treatment during the winter 2014–2015, in microcosms positioned in a greenhouse at the Tour du Valat Research Center, Camargue, Southern France. Energy densities and remaining proportions of initial seed biomass are the predicted values from the best models of tables 1 and 2. Seeds were collected for analysis after 123 days of experiment.

	Energy density per gram seed at the beginning of the winter (kJ/g)	Energy density per gram seed at the end of the winter (kJ/g)	Remaining proportion of initial seed biomass at the end of the winter	Final energy available at the end of the winter from an initial 1gram seed (kJ)	Gross energy loss through the winter
Rice dry	16.5	17.0	0.538	9.146	62.3%
Rice flooded	16.5	17.8	0.376	6.693	59.4%
Weedy rice dry	16.9	17.0	0.734	12.478	26.2%
Weedy rice flooded	16.9	17.8	0.547	9.737	42.4%
Barnyardgrass dry	18.3	18.5	0.621	11.489	37.2%
Barnyardgrass flooded	18.3	19.3	0.567	10.943	40.2%
Sea clubrush dry	19.7	20.0	0.765	15.30	22.3%
Sea clubrush flooded	19.7	20.0	0.747	14.94	24.2%

Besides energy density, it is a fact that seeds vary in size, morphology, digestibility and chemical composition among species, all of which influence potential energy gain for waterfowl (Hagy & Kaminsky, 2015). The true metabolizable energy of seeds has already been quantified in earlier studies, and found to be 3.34 kcal/g for cultivated and weedy rice (Reinecke *et al*., 1989), 2.61 kcal/g for barnyardgrass seeds (Checkett *et al*., 2002) and 3.12 kcal/g for sea clubrush (Legagneux, 2007). Although rice would therefore seem more digestible than the weed seeds, this suggests the latter are, for a similar seed mass, a more profitable food resource for wintering waterfowl owing to the overall lower gross energy content of cultivated rice. Some authors also highlighted that rice seeds alone cannot provide a balanced diet, as they have high carbohydrate contents and are poorer in protein, fat, potassium, calcium and nitrogen than moist-soil seeds (Eadie *et al*., 2008; Stafford *et al*., 2010). The greater size of rice seeds compared to weeds may potentially (partly) compensate for the lower energy content of the former, through more efficient foraging by the ducks (e.g. Van Eerden and Munsterman, 1997). This can explain why rice, although not as energy-rich than some weed seeds, nevertheless represents a significant part of the wintering duck's diet wherever available (e.g. Brochet et al., 2012). Apart from weedy rice, which may deteriorate more rapidly if flooded, our experiments finally suggest that flooding harvested rice fields would not cause a faster decline of the energy available to waterfowl compared to dry conditions.

From the point of view of the farmers, what matters the most is whether the decreased seed mass and gross energy recorded above would translate into a reduced development of the weeds during the following cropping season. We did observe a general decrease in seed viability from post-harvest (October) to late winter (February): while most seeds were initially alive, only 56.9% were so on average at the end of the experiment. This may be related to the general loss of energy per seed we recorded (seed energy density per gram slightly increased while seed mass markedly declined over the winter). In fact, the results above indicate a similar rate of gross energy loss between flooded and dry conditions for most seeds (Table 4), and viability of such seeds also declined at similar rates whatever the treatment received by the seeds, suggesting a mechanistic link between the two parameters. The only exception was cultivated rice, whose viability was reduced to ca. 13% in flooded trays compared to only 54% in dry ones. Rice was also the species that lost the most mass across the experiment and had the lowest remaining energy content at the end of the winter, especially under flooded conditions.

As opposed to earlier studies, our results suggest limited impact of winter flooding on weed seed viability, while Fogliatto *et al*. (2010) recorded a 95% decrease for weedy rice in flooded fields compared to 26-77% if unflooded, and the same figures in Baek & Chung (2012) were 49% versus 10%. In our study, the average 96.93% [92.98–100] viable weedy rice seeds showed a reduction of 22.8% [12.5–37.8] of their viability under dry condition, versus 43.8 [29.7–59.0] if flooded, which was not significantly different. It is a fact that the tetrazolium test we used to assess seed viability is relatively difficult to interpret (Justice, 1972), so that the great variability in viability rates may have prevented the detection of a significant difference in weedy rice. It is also possible that the climatic conditions this winter were relatively comfortable for the seeds, so that overall mortality was low. In particular, the 2014-2015 winter was particularly mild in the Camargue, with a month of November that was the hottest since 1963, the temperature of December above the average (8.45°C versus 7.2°C) and only 4 days of frost in December and January (frost above -1°C) (P. Chauvelon, Tour du Valat, unpublished data). Colder weather may have a differential effect on the seeds, which

could potentially suffer greater mortality under flooded conditions if the water freezes (Baek & Chung, 2012).

To summarize, our study provides another demonstration that rice and weed seeds lose mass and viability during the winter. Our experiments in microcosms showed that seed energy density remained relatively constant, but the gradual loss in seed mass led to a declining gross energy per seed, which may have been the cause of decreased seed survival. Gross energy loss for a given seed species was generally similar between flooded and dry conditions, as was seed viability in weeds. As opposed to earlier studies, we did not observe post-harvest flooding to be a beneficial practice for farmers in terms of reduction of the seed bank viability by the end of the winter (Street and Bollich, 2003; Manley *et al*., 2005; Anders *et al*., 2008; Fogliatto, Vidotto & Ferrero, 2010; Baek & Chung, 2012). This cannot therefore be recommended specifically for this purpose, but it remains to be established whether seeds would sprout and seedlings would grow to a similar extent after a flooded versus dry treatment. In any case, other studies showed that winter flooding could bring other benefits to farmers in terms of straw disposal (Brogi *et al.,* 2015) or income from hunting (Niang *et al*., submitted). Our results also suggest that post-harvest practices would hardly affect energy availability to ducks, which would decrease across the winter in any case. However, water is necessary for these birds to efficiently forage (Guillemain *et al*., 1999), so that this practice should be promoted to increase waterfowl habitat availability. Several countries have already recognised the potential of ricefield flooding to create suitable habitat for wintering waterfowl, and help farmers to implement this technique via financial incentives such as agri-environment schemes (Pernollet *et al.*, 2015b). The present results suggest that gross energy available to ducks would not be reduced through seed deterioration by this practice, which should therefore be further implemented in wider geographic areas.

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Article 5:

Waterfowl foraging in winter-flooded ricefields: Any agronomic benefits for farmers?

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REPORT

Waterfowl foraging in winter-flooded ricefields: Any agronomic benefits for farmers?

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Abstract Winter-flooding of ricefields provides foraging habitat to waterfowl, which in return may bring agronomic benefits to farmers. Our study experimentally tested the effect of mallards (*Anas platyrhynchos*) on the standing stalks and weed seed bank in the Camargue (France), both of which present major challenges for farmers. Three duck densities were tested: (D1) 5 ducks ha^{-1} (historical nocturnal density), (D2) 23 ducks ha^{-1} (present nocturnal density), and (D3) 300 ducks ha^{-1} (Asian rice-duck farming density). The ducks reduced the stalks significantly: −27 % (D1), −52 % (D2), and −91 % (D3). Conversely, they decreased the number of seeds by only 3 % (D3) and the seed mass by about 21 % (D1 and D3), which was not significant. Besides they had no effect on seed species richness. This study clearly demonstrates that the winter-flooding effect on straw decomposition can be enhanced by waterfowl foraging, hence showing an agronomic benefit from ducks to farmers. However, there was no clear effect in terms of seed bank reduction.

Keywords Rice · Straw disposal · Waterfowl · Weeds · Winter-flooding

INTRODUCTION

Waterbirds provide important ecosystem services, both cultural (e.g., birdwatching, leisure hunting) and provisioning (meat, eggs, feathers, etc.). They can also contribute to maintaining wetlands' biodiversity through dispersal of aquatic organisms and seeds, grazing, or pest control (Green and Elmberg 2014). Agroecology highlights the importance of creating agricultural systems that build on natural ecosystems for sustainability (Gliessman 2007), hence largely relying on existing services provided by some elements of these ecosystems.

Associating rice (*Oryza sativa*) and duck farming is a traditional Chinese practice, recently formalized as "Integrated Rice Duck Farming" and widely spread throughout Asia (IRDF, Furuno 2001). IRDF is a synchronic farming system: interactions between crops and livestock are promoted within the same space, at the same time. One-week-old ducklings are introduced at a density of 150–300 ducks ha^{-1} in fenced paddy fields one week after planting the rice seedlings, or about 23 days after direct sowing. The rice and the ducks grow together in the field in a mutually beneficial way: the rice field provides (1) food resources in the form of waste rice and weeds (fodder and seeds), rice pests and other aquatic organisms, (2) water habitat, and (3) shelter to the ducks. In return, the ducks provide (1) weeding, (2) pest control, (3) nutrients, (4) ploughing and muddying, and (5) physical stimulation of the plant resulting in growth hormone production (Furuno 2012). Traditionally, ducks were also introduced into ricefields after harvest to feed on waste rice (Suh 2014a). IRDF differs from conventional rice cultivation as the ducks perform some tasks that usually require chemical addition, while here resource utilization is maximized in a low input strategy (Furuno 2012). Adaptations of this ancestral approach to farming now exist throughout Asia (Hossain et al. 2005; Rutz and Zingerli 2009), although local constraints (climatic, labor, species-related, or sanitary concerns such as fear of Avian Influenza Viruses) may hinder its actual spread (Gilbert et al. 2007; Suh 2014b).

Waterfowl and rice farming are also linked in North America, albeit in a different context since it is driven by concern for wild waterfowl conservation and the threat of loss of their habitat. Natural wetlands are drastically disappearing; more than 50 % of the world's wetlands were

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lost during the twentieth century and 56–65 % of these were converted to agricultural land in North America and Europe (Finlayson and Davidson 1999). Flooded ricefields can play an important role in supplementing natural wetland resources as foraging grounds for waterfowl (Elphick and Oring 2003). In North America, ricefields are flooded during the winter period to attract waterfowl as part of a habitat management scheme (Eadie et al. 2008). In California, more than 40 % of ricefields are flooded during winter (Miller et al. 2010). The post-harvest practice in this state was encouraged by the prohibition of rice straw burning (California Rice Straw Burning Reduction Act, Bird et al. 2000a). Winter flooding contributes to (1) increasing straw decomposition rate; (2) decreasing weed seed viability by inhibiting their germination and postponing their winter growth; (3) limiting soil erosion; (4) retaining sediments and nutrients; (5) improving soil and water quality; and (6) reducing need for spring tillage (Manley et al. 2005; Anders et al. 2008). Moreover, the waterfowl attracted by flooding can further enhance the benefits triggered by implementing this post-harvest practice. Their trampling and foraging can lead to increased straw decomposition (Bird et al. 2000a; Manley et al. 2005), as well as decreased weed biomass in spring (van Groenigen et al. 2003; Manley et al. 2005).

Indeed, disposal of rice straw is a challenge because of its high silica content which makes it resistant to decomposition and abrasive, resulting in increased wear and tear of machinery (Monier et al. 2009). Straw incorporation produces a greater pool of soil organic nitrogen (Bird et al. 2000b) and winter flooding has been proven to further increase crop nitrogen uptake, possibly reducing the need for fertilization (Eagle et al. 2000). Weeds are also a challenge for rice farmers as they represent a major cause of yield loss (ca. 10 % of total loss on average, Oerke 2006), and thus are one of the main obstacles to conversion to organic farming (Mailly et al. 2013).

In the Camargue Rhône Delta (Southern France), 75 % of the residual rice straw still undergoes burning. This practice is currently tolerated, but a change of policy may occur in the future due to the air pollution it causes (Monier et al. 2009). Up until now, winter flooding after rice harvest is done mainly to attract waterfowl for hunting and thus is used relatively little at the regional scale (ca. 9 % of rice area, Pernollet et al. 2015) in spite of the opportunities that this practice could represent in terms of biodiversity and agronomic issues.

The general objective of this research was to assess the agronomic benefits that French farmers might expect from the use of wild waterfowl on their winter-flooded ricefields. Indeed, no comparable study to those conducted in North America has been carried out in Europe so far to determine the possible effects of ducks. The climatic conditions, the use of different rice varieties over somewhat different soils, the differences in weed species, the fact that the landscape is more fragmented in the Camargue, and that the waterfowl use the ricefields mainly as nocturnal foraging grounds may all potentially lead to different conclusions. Additionally, previous studies may have underestimated total waterfowl use of ricefields since surveys were made during the day-time (e.g., Tourenq et al. 2001 for Europe; Elphick and Oring 2003 for the US). In particular, we aimed at quantifying (1) the trampling effect of ducks on the density of standing stalks and; (2) the foraging effect of ducks on seed abundance and species richness, considering both rice leftovers and weeds. Our predictions were that ducks would significantly reduce the number of standing stalks per experimental plot, especially at high density, and we expected they could significantly reduce the seed bank, especially for the larger seeds (>1.5 mm) which dabbling ducks normally prefer (Guillemain et al. 2002).

MATERIALS AND METHODS

Experimental plots

The research was carried out in the Camargue, the delta of the Rhône River, in Southern France. This region of about 145 000 ha comprised 60 000 ha of wetlands (Tamisier and Dehorter 1999) and 15 300 ha of cultivated rice in 2011, which represents 62 % of the agricultural area, the rest being dry crops and pastures (Regional Nature Park of the Camargue 2013). This combination of habitats makes this territory a very important site for waterfowl, especially during winter. The Camargue is the most important winter quarter at the national scale for four of the seven European dabbling duck species (i.e., mallard *Anas platyrhynchos*, common teal *A. crecca*, Eurasian wigeon *A. penelope* and Gadwall *A. strepera*, Heath and Evans 2000). The Camargue is almost the only area in France where rice is cultivated, owing to the climatic requirements of this culture. Ricefields are traditionally flooded between seeding and harvest, i.e., from April to September, then kept dry either in stubble, early disked, or ploughed during winter.

The experiments were carried out in a 2.7 ha rice field located at the center of the delta (Le Sambuc: 43°32′N, 4°43′E). This area corresponds to the mean size of ricefields in Camargue (2.5 ha, Mouret, pers. comm.). This field is cultivated conventionally (the preponderant method, as only 6 % of the Camargue rice is organic), with straw being crushed after harvest. It was experimentally flooded from mid-November 2013 to mid-February 2014 (average water depth: 15.5 cm) and was not hunted. The year preceding the experiment (winter 2012–2013), this field was under organic cultivation, it was dried at the

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beginning of October and the straw was burnt after harvest. The field is close to major duck day-roosts in the Tour du Valat Nature Reserve (1.7 km flight distance, Guillemain et al. 2010), and weekly nocturnal counts during the same winter demonstrated that it was used by wild dabbling ducks as a nocturnal foraging ground. This experimental field was thus considered as representative of a typical Camargue rice field.

Experimental protocol

The tests were performed from January 21st to February 19th 2014, i.e., when wintering ducks are close to their maximum seasonal numbers in Camargue (Tamisier and Dehorter 1999). We used wing-clipped domestic mallards to mimic the effect of wintering wild ducks. In addition to the pre-treatment situation in each case (density D0, no ducks in the enclosure yet), three densities of ducks were used to represent three field situations. Two of the densities are nocturnal densities found naturally in Camargue during the winter: (1) 5 ducks ha^{-1}, the historical density recorded in the Camargue by Pirot (1981), (2) 23 ducks ha^{-1}, the nocturnal density presently observed in the Camargue ricefields (mean value recorded during nocturnal surveys on 32 post-harvest flooded ricefields between November 2013 and January 2014, Pernollet et al., unpubl.). The third density corresponds to the artificial density of ducks introduced in ricefields during the growing season as part of the Asian cultivation technique: (3) 300 ducks ha^{-1}, as is practiced in IRDF (Furuno 2012).

For this purpose, the number of ducks introduced to the experimental plots for each of the three above densities was determined using the formula: $N = (F \times D \times A)/(10\,000T)$, where N is the number of experimental ducks to release on the plot; F is the time the wild ducks normally spend foraging during a complete winter (in hours); D is the density tested (in ducks per hectare, transformed into ducks per m^2); A is the area of the experimental plot (in m^2); and T is the time the experimental ducks were left in the enclosure (in hours).

Considering that in the Camargue wintering wild ducks forage for ca. 10 h per 24 h, almost exclusively at night (Tamisier and Dehorter 1999), that the wintering season spans from November to February (the period during which the ducks are present in Camargue and the ricefields are available for foraging i.e., between rice harvest and ploughing), the total time spent foraging in a given rice field is $F = 10\text{ h} \times 30\text{ days} \times 4\text{ months} = 1200\text{ h}$. To measure the impact that the IRDF density would have if practiced in the Camargue, we considered that similarly the ducks would forage 10 h per 24 h and so 1200 h over the whole season.

The size of the experimental plots was set at $A = 9\ m^2$. The time that the ducks were left on the plots was set at: $T = 2$ h for the first two densities and $T = 20$ h for the IRDF density (so as to limit the number of experimental ducks used in a limited area). The number of ducks in the enclosure and the duration of the experiments are given in Table 1.

Table 1 Experimental settings specifying the duration of the experiment and the number of ducks for each density

Real duck density	Duration of the experiments	Number of ducks in enclosure
D0 = 0 ducks ha^{-1}	T0 = 0 h	N0 = 0 ducks
D1 = 5 ducks ha^{-1}	T1 = 2 h	N1 = 3 ducks
D2 = 23 ducks ha^{-1}	T2 = 2 h	N2 = 12 ducks
D3 = 300 ducks ha^{-1}	T3 = 20 h	N3 = 16 ducks

For each of the three duck densities, the following protocol was applied: first, a new 9 m^2 enclosure was set up in a previously unused part of the winter-flooded ricefield. Enclosures were scattered uniformly over the field. Replicates for D1 and D2 were performed simultaneously within a single 2 h period in two separate enclosures. Each D3 trial was performed over two periods of 10 h during two consecutive days. The ducks were locked in overnight and did not receive supplementary feeding. Behavioral observations confirmed they were as a consequence actively foraging during our experimental tests. We alternated D1/D2 and D3 replicates, the latter being initiated at 3-day intervals. Once the enclosure was set up, seed bank samples were taken from nine soil cores (4.5 cm-diameter to 4 cm-depth) uniformly spread across the plot in a grid shape [at least 30 cm away from the edge and 80 cm (±10 cm) away from each other]. The number of standing stalks was recorded in a 25 × 25 cm quadrat randomly thrown ten times in the enclosure. These pre-treatment measurements correspond to density D0 (no ducks). N1, N2, or N3 ducks were then introduced for T1, T2, or T3 h. Because the ducks needed some time to adapt to their new environment, the experiment started when the ducks started to behave in a consistent way, i.e., initiated foraging or preening rather than swimming along the fences. To make sure the ducks were feeding, we observed them directly at a safe distance and also video-recorded the experiments during the first week. At the end of each trial, nine new soil samples were taken following the same protocol as above. Each post-duck soil sample was taken within a 10 cm radius of the associated pre-duck sample marked by a wooden stick. Soil samples were later sieved to 300 µm and dried at 70°C; seeds were then identified and counted per species using a binocular magnifier (W-PI 10×/23) and reference literature (Cappers et al. 2006). Weedy rice and cultivated rice were not differentiated. The number of remaining standing stalks in the plot was also recorded after the ducks were removed, with the same protocol as before duck introduction. The general aspect of the straw pre- and post-duck treatment was also captured by taking

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photographs. The same experiment was repeated six times for each duck density.

An associated control plot, without any introduction of ducks, was set up beside each enclosure to assess representativeness of our plots in terms of stalk samples.

Statistical analyses

We first tested whether our experimental plots were representative of the whole field in terms of stubble density by comparing the number of standing stalks per quadrat in the enclosures to the number in the associated control plot with a pairwise Student t test. This yielded a non-significant result ($t_{179} = 0.51$, $p = 0.61$), indicating no statistically significant difference of means. We then proceeded with the analyses by testing for an effect of density of ducks on the number of standing stalks in the enclosures, using a generalized linear mixed model (GLMM) with a negative binomial distribution (package glmmADMB, glmmadmb function), after having checked for overdispersion ($\mu = 17.8$, $\sigma^2 = 171.2$). The data used for the analysis consisted of 360 (3 duck densities × 10 quadrats/plot × 2 pre- and post-treatments × 6 replicates) measures of the number of standing stalks. Density was included as a four level fixed factor (D0 corresponding to the pre-treatment, D1, D2, and D3 corresponding to the post-treatments), and plot (i.e., 1–18 since we did 6 replicates for each of the three duck densities) was included as a random factor. The fit of the model to the data was checked by performing an analysis of variance (package car, anova function) comparing it to the null model. Post hoc pairwise tests (package multcomp, glht function, Tukey test) were performed to compare the mean number of stalks among the three pre-treatment situations (the three D0 later associated with different densities of ducks) and among the post-treatment situations, i.e., D1, D2, and D3.

To determine if there was an effect of density of ducks (D1, D2, and D3) on the seed bank, we similarly compared seed abundance and richness before and after the introduction of the ducks for each density tested. We used a GLMM with a negative binomial distribution on the number of seeds after having checked for overdispersion ($\mu = 70.3$, $\sigma^2 = 1645.4$). Since there was no overdispersion ($\mu = 6.5$, $\sigma^2 = 4.0$) for the number of species, we performed a GLMM with a Poisson distribution. The data used for the analysis consisted of 324 measures (3 duck densities × 9 cores/plot × 2 pre- and post-treatments × 6 replicates) of the seed bank. The same mixed factors were chosen as for the stalks.

Using a reference publication complemented by unpublished Camargue data (Arzel et al. 2007; Brochet and Mouronval, unpubl.), we computed the mean mass of each seed species per core from the number of seeds. We log-transformed the seed mass and added a constant (constant value = 2) to attain a normal distribution, then performed a GLMM with a Gaussian distribution to test for potential differences in mean seed mass, with the same mixed factors as before.

Finally, we renewed the three previous analyses (on seed abundance, specific richness and mean seed mass) taking out the seeds under 1.5 mm in size, as mallards may avoid such small seeds (Guillemain et al. 2002). The mean size of each seed species was found in the literature (Cappers et al. 2006).

All statistical analyses were performed using R software (R version 3.1.0 beta, R development Core Team 2014). Results are expressed as mean ± standard deviation (SD) throughout the text, and the impact of ducks on stalks and the seed bank was expressed in percentage. Mean values pre- and post-treatment (as well as their SD) stand for the averages computed over $n = 6$ trials in each situation, each trial value being the mean of all 10 stalk counts or 9 core samples.

RESULTS

Stalks

The GLMM showed that duck activity had a significant effect on the number of standing stalks. Indeed the comparison to the null model proved significant (deviance = 280, df = 3, $p < 0.001$). The analyses of effect sizes indicated significant differences ($p < 0.001$) between each duck density and D0 (Table 2), i.e., duck activity reduced the density of standing stalks. The post hoc Tukey tests indicated no significant difference in mean number of standing stalks before treatment among the three duck densities (i.e., the three sets of D0 values), but showed a significant difference ($p < 0.001$) between the three post-treatment situations D1, D2, and D3 (Fig. 1).

When expressed in percentages, the mean decrease in number of standing stalks was of −27 % (±16 %) for D1 compared to its associated D0, −52 % (±15 %) for D2, and −91 % (±3 %) for D3. The impact of the ducks was clearly visible on the number of standing stalks in the experimental plots (Fig. 2).

Weeds

The core samples revealed the presence of 36 different weed species in addition to rice in the experimental plots. At least five species of five genera occurred in more than 50 % of the samples (Table 3).

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Table 2 Generalized linear mixed model (negative binomial distribution) testing the effect of duck density (D0, D1, D2, and D3) on the mean number of stalks per 175 cm^2. In each model, the plot (3 densities × 6 replicates = 18 plots) was included as a random factor. See text for statistics of the complete model. The table here shows the effect sizes, which correspond to comparisons of mean density values for D1, D2, and D3 to the mean value for D0, i.e., stalks density pre-duck treatment

Fixed effects	Estimate	SE	p value
Model : Number of stalks ~ duck density + (1 | plot), family = negative binomial			
Intercept (D0)	3.2	0.05	$p < 0.001$
Density 1	−0.4	0.09	$p < 0.001$
Density 2	−0.7	0.09	$p < 0.001$
Density 3	−2.4	0.12	$p < 0.001$

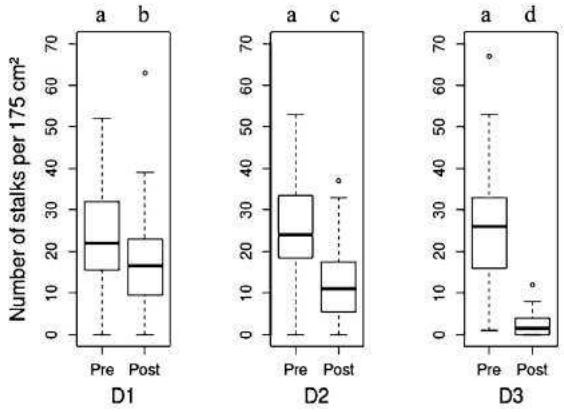

Fig. 1 Number of stalks per quadrat before and after duck treatment for each duck density (D1 = 5 ducks ha^{-1}, D2 = 23 ducks ha^{-1}, D3 = 300 ducks ha^{-1}). For each density before and after duck treatment, the figure represents the minimum, the first quartile, the median, the third quartile, and the maximum. Boxes with *different letters* differed significantly after post hoc Tukey tests

The GLMM showed no significant effect of the ducks' foraging on the number of seeds (deviance = 2.3, df = 3, $p = 0.51$). At density D3, the mean number of seeds only showed a non-significant 3 % (±32 %) decrease after the duck treatment compared to the initial situation.

There was a decrease of the mean seed mass before and after the ducks for D1 and D3: respectively, −17 % (±68 SD) and −25 % (±51). Concerning D2, the tendency was an increase of the seed mass, although with a very high SD: 81 % (±211). However, the linear mixed model showed no significant effect of density on the mean seed mass (deviance = 4.2, df = 3, $p = 0.24$).

As with seed mass, the GLM showed no significant effect of the ducks on the species richness of the samples, for the three duck densities tested (deviance = 1.3, df = 3, $p = 0.73$).

The same analyses performed on a subset of the data without the smaller seeds (<1.5 mm) yielded the same results (not shown).

DISCUSSION

Ducks had a very clear effect on the standing stalks, most likely due to their trampling, while the consequence of their foraging on the seed bank of weeds and rice leftovers was not significant.

The ducks particularly reduced the amount of standing stalks when they were at higher densities. Their impact was almost doubled between the historical (5 ducks ha^{-1}), and the natural density (23 ducks ha^{-1}), respectively, −27 and −52 %, and again from the natural density to the IRDF density (−91 %). Therefore, foraging of wild ducks on winter-flooded ricefields can greatly contribute to getting rid of standing stalks. High densities of ducks may reduce stubble because the trampling pushes the straw underwater, leading to its incorporation into the soil and increased decomposition (Bird et al. 2000a).

The present results are novel, since stalks have not been targeted in previous studies, which have concentrated more on lying residual straw. Indeed the latter was shown to decrease by 27–41 % in flooded ricefields compared to unflooded (Bird et al. 2000a), and up to 41–68 % after disking plus flooding (Manley et al. 2005). In addition to submersing the stalks, the trampling of the ducks has a direct effect on the straw by flattening and cracking it, resulting in an increased soil contact and greater accessibility for microbial decomposers (Bird et al. 2000a). These authors quantified the additional effect of waterfowl (with a density of 33 birds ha^{-1} over a 180-day-long season) as a 78 % increase in straw decomposition in untilled plots and a 18 % increase in wet-rolled compared to fields without waterfowl. There is little information on the impact of ducks on post-harvest residual straw in Asia, since the interest there is focused on duck benefits during the growing season (Furuno 2012; Suh 2014b).

Winter flooding by combining the action of standing water and waterfowl activity could provide economic benefits to farmers, which has been evaluated in the US. Savings in the form of reduced tillage requirements and preparation costs for seeding (Bird et al. 2000a; Manley et al. 2005) can reach up to US $22–63 ha^{-1} (Stafford et al.

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Fig. 2 Standing stalks before (*left*) and after (*right*) duck treatment at the three duck densities D1 = 5 ducks ha^{-1} (*top*), D2 = 23 ducks ha^{-1} (*middle*), D3 = 300 ducks ha^{-1} (*bottom*) (Photos by Anne Brogi)

2010). Moreover, US \$34.22 ha^{-1} could be saved by eliminating two disking passes in autumn (Manley et al. 2005). Getting rid of residual straw after harvest by chopping, ploughing or disking can cost up to US \$125 ha^{-1} (Bird et al. 2000b). Such savings could potentially also be made in Europe. An estimate of the financial benefits that ducks can provide farmers in France needs to take into account the high cost of pumping for flooding and draining into the river, which has never been done before. A detailed cost-benefit analysis is underway to assess whether this represents an economically realistic option for Camargue rice farmers (Pernollet et al., unpubl.).

In Camargue, 40 weed species are commonly recorded in ricefields (Marnotte et al. 2006). Out of the 36 weeds found here, four of the most frequent ones are considered to be major weeds of ricefields in the area (*Heteranthera*

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Table 3 Seed species found in the samples, with occurrence (% of core samples containing a given species), relative abundance (%), and relative dry mass (%) as computed from seed numbers and reference seed masses

Species	Occurrence (%)	Relative abundance (%)	Relative mass (%)
Chara sp.[a]	99	84	12
Heteranthera limosa	87	5.9	1
Ranunculus sceleratus	70	2.5	3
Scirpus maritimus	68	1.9	29
Phragmites australis	52	1.5	1
Ranunculus baudotii	35	0.7	0.6
Cyperus fuscus	33	1.1	0.03
Eleocharis uniglumis	18	0.3	0.7
Echinochloa crus galli	17	0.3	3
Scirpoides holoschoenus	16	0.3	0.4
Trifolium campestre	15	0.2	0.4
Potamogeton pusillus	10	0.2	0.5
Najas indica	9	0.2	0.2
Suaeda fruticosa	9	0.1	0.2
Oryza sativa	8	0.4	46
Carex vulpina	8	0.1	0.5
Chenopodium album	6	0.1	0.3
Ranunculus sardous	6	0.1	0.7
Lolium perenne	5	0.1	0.02
Salicornia europaea	5	0.1	0.1
Trifolium repens	3	0.1	0.1
Rubus fructicosus	3	0.05	0.5
Zannichellia palustris	2	0.04	0.1
Arthrocnemum glaucum	2	0.03	0.03
Poaceae sp.[a]	2	0.04	0.2
Melilotus albus	2	0.03	0.1
Juncus effusus	1	0.01	0.001
Polygonum aviculare	1	0.01	0.1
Alisma sp.[a]	1	0.01	0.01
Baldellia ranunculoides	1	0.01	0.01
Euphorbia helioscopia	1	0.01	0.1
Galium palustre	0.3	0.005	0.01
Leerzia oryzoides	0.3	0.005	0.03
Rumex crispus	0.3	0.005	0.01
Schoenoplectus mucronatus	0.3	0.005	0.02
Schoenoplectus tabernaemontani	0.3	0.005	0.04
Scirpus lacustris	0.3	0.005	0.01

[a] Seeds of *Chara*, *Alisma* and *Poaceae* could not be identified to species, but a single species in each genera/family appeared to dominate in our samples

limosa, *Phragmites australis*, *Scirpus maritimus*, and *Echinochloa crus galli*), and two as secondary ones (*Ranunculus sceleratus* and *Cyperus fuscus*, Marnotte et al. 2006). The 11 most frequent seeds we found were proven to be part of duck diet in the Camargue (Brochet et al. 2012). Moreover, nocturnal duck counts carried out during the same winter as our tests (November 2013–February 2014) demonstrated that this experimental field was used by dabbling ducks as a nocturnal foraging ground: we observed a total of 348 mallards and 54 teal during the 13 weekly nocturnal counts, with a mean density of 12 (±20) ducks ha^{-1} $night^{-1}$ (Pernollet et al., unpubl.). The seed bank we recorded was therefore attractive to wild birds. With the knowledge that dabbling ducks are mainly granivorous during winter (Guillemain et al. 2002), we were confident it would be used by the ducks, while at the same time being a problem for the farmer as a source of weeds. Prior to the test period, the bred ducks we used had been fed with wheat seeds and had free access to partly flooded grassland where they could feed on seeds. Consequently, they would have been able to identify seeds as potential food and were observed eating in the plots during the experiment. It is possible that the ducks were in fact partly eating macroinvertebrates; however we did not measure the availability of these in our samples and we do not have any conclusive data for Camargue winter-flooded ricefields in January. In any case, whatever the reason behind this pattern, our results clearly show that despite their active foraging the ducks at the density we used were not able to significantly deplete the seed bank.

Flooding itself can affect the seed bank by increasing the decomposition rate of some seeds (Stafford et al. 2005). The decaying of seeds is triggered by a combination of high moisture content and alternate low and high temperatures (Fogliatto et al. 2010). It has been demonstrated that winter flooding is highly effective in controlling some weeds such as weedy rice (*Oryza sativa* L., Fogliatto et al. 2010) and in inhibiting dormancy break of other seeds such as the exotic *Heteranthera limosa* (Baskin et al. 2002). Greer et al. (2009) attributed 44–47 % of waste rice seed loss over the winter to deterioration due to flooded conditions. Another factor of seed bank decrease may potentially be waterfowl foraging. However, we did not detect any significant effect of the ducks on the weed seed bank. These results are in contrast to previous studies: Li et al. (2012) found a decline of the number of weed species (from 38 to 21) and of the weed seed bank density of more than 90 % which they attributed to foraging by ducks. Other studies have either measured the effect of waterfowl on waste rice seeds available after harvest or on the grassy weed biomass of the next growing season. Measuring the weed seed bank, we expected greater effects, since not all the seeds present in winter will germinate during the subsequent growing season. Greer et al. (2009) estimated that wild waterfowl consumed between 25 and 48 % of waste rice seeds. Concerning weed biomass, the estimated decrease was of 48 % with a medium waterfowl activity (0–21.3 birds ha^{-1}) during the winter (van Groenigen et al. 2003). When ducks are released at high densities in

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ricefields during the growing season in Asia (IRDF), their estimated effect on the weed biomass varies from a 58 to 98 % reduction (Hossain et al. 2005; Yu et al. 2008). The mallards we used were approximately the same size as the ducks in IRDF which normally uses "Aigamo" ducks, a crossbreed between mallards and pacific black ducks (*Anas superciliosa*), although some farmers may use larger ducks such as white pekin ducks (*Anas platyrhynchos domestica*). Contrary to Guillemain et al. (2002), we did not detect any difference when focusing on seeds over 1.5 mm, which should be preferably consumed by mallards (Brochet et al. 2010).

The lack of significant effects of the ducks on the seeds may be due to the very patchy distribution of the seeds in the ricefields, resulting in a highly variable number of seeds per core sample. Such a high intra-field variability in seed distribution may have prevented us from detecting any potential effect of the ducks if this was of limited magnitude, given the limited number of replicates that could practically be performed.

There was an overall low abundance of seeds in the field chosen for the study (11 g m^{-2}), which was only half of the mean winter seed biomass of 21.2 g m^{-2} found in Camargue by Tamisier (1971). More recent studies in Spain have shown that similarly crushed and flooded fields have a waste rice density of 24.5 g m^{-2} (Toral 2011), while in North America the values range from 6.6 to 67.2 g m^{-2} (Stafford et al. 2010). In any case, we found an abundance of seeds well above the giving-up density of 5 g m^{-2}, under which waterfowl are considered to cease foraging (Reinecke et al. 1989; Greer et al. 2009). Therefore, ducks should have considered the experimental plots as a valuable feeding habitat.

It may seem surprising that ducks had such a limited effect on the seed bank at densities as high as practiced in IRDF (300 ducks ha^{-1}), which is much greater than the historical and the natural densities recorded in France (5 and 23 ducks ha^{-1}, respectively). It is likely that the ducks are more efficient in Asian IRDF because they are put in the ricefields during the growing season, as opposed to winter here. During the growing season, the ducks have a greater impact on the weeds since they have a triple action: they prevent the seeds from germinating by provoking water turbidity, they trample the plantlets, and they feed on the seedlings (Zhang et al. 2009; Furuno 2012), hence directly acting on grassy weeds that are competing with the cultivated rice.

CONCLUSION

The present study suggests that waterfowl may not always have a significant effect on the weed seed bank during the winter. Therefore, they may not significantly impact the weeds, which are a major limiting factor of rice cultivation and conversion to organic agriculture. However, the ducks provide a significant effect in terms of stubble reduction, which is also an important issue for rice cultivation, even more so if straw burning becomes banned in the future. Flooding ricefields during winter, to make them available to waterfowl, could thus be a way of combining conservation of biodiversity and provision of agronomic benefits to farmers, and should be promoted.

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IV. DISCUSSION

The "first fruit" made with duck feathers by Samuel Lei, California

IV.1 Could a change in postharvest agricultural practices be simultaneously beneficial to rice farmers and wintering ducks?

To investigate whether **'win–win' agricultural scenarios for rice producers and waterfowl conservation could exist within intensive European rice production areas,** especially in France, **we relied on a variety of approaches** including a literature review (**Chapter I, Article 1**), empirical (**Chapter II, Articles 2 and 3**) and experimental studies (**Chapter III, Articles 4 and 5**) in the general conceptual framework of optimal foraging by birds, agro-ecology and ecosystem services.

Reviewing the scientific literature on rice farming and duck conservation worldwide, we identified winter flooding of rice fields as a valuable habitat management, providing potential benefits to ducks through the direct use of agricultural fields as wintering habitats, and to farmers through the increase of straw decomposition rate and the reduction of weed seed viability by water and waterfowl action (**Article 1**). The studies implemented here to test whether similar benefits could be expected in Europe and most particularly in France confirmed that winter flooding of harvested rice fields is indeed a valuable management option, with identified benefits for both wild ducks and farmers. We demonstrated a general pattern of positive correlation between ricefield winter flooding area and the size of regional wintering duck populations along their flyway in south Western Europe (**Article 2**). Through the study of the processes at play at a more local scale, we concluded that any flooded non-ploughing agricultural management would actually be suitable to wintering waterfowl in Camargue, as any of these options would readily allow waterfowl accessing the abundant seed food stocks (**Article 3**). Relatively simple management procedures such as winter flooding can therefore be adopted to improve the usability of these habitats for wintering waterfowl. In return, rice farmers can expect straw disposal to be enhanced by the presence of foraging waterfowl in winter flooded fields (**Article 5**). Based on these ecological and agronomical results, we conclude that winter flooding should be promoted for waterbirds in Camargue and anywhere else it is technically feasible. When implemented through Agri-Environment Schemes (AES) in Spain such a practice has proven to be an efficient measure, quickly translating into improved local duck population trends (**Article 2**).

Although the results of this research project are clear and the various facets of the analyses are consistent with each other (compare the various papers), this study has its own limits.

The literature review only met 14 of the 27 methodological criteria defining a systematic review according to Roberts et al. (2006) (**Article 1**). Among the criteria that were not met is for instance the detailed explanation for inclusion/exclusion of studies, the performing of a meta-analysis, and the sensitivity analyses. Several of these limitations are actually due to the literature sources themselves, which often did not provide proper quantitative information and/or were difficult to compare to each other owing to their own very qualitative narrative style. Nevertheless, particular attention was paid to consider both negative and positive interactions between rice farming and duck conservation, to cover all the geographic areas and to mix sources of information as much as possible, as a fully systematic review would require. The literature review also allowed identifying evidence gaps or areas lacking knowledge to tackle the relevant issues initially defined, and provided recommendations for future topics still requiring investigation. Nevertheless, this review did not allow us to answer all the initial questions, particularly those related with potential

conflicts between ricefield winter flooding for waterfowl and alternative practices aiming at other environmental goals (e.g. reduction of greenhouse gas emissions). Still, it provided a valuable basis within which to frame the overall thesis. In particular, this called for a precise examination of the potentially mutually beneficial relationships between farming practices and waterfowl conservation within any given study area (**Chapters II and III**), as well as a proper economic evaluation of the balance between expected costs and benefits of winter flooding for the rice farmers and the local society, which is presented below (**Article 6**).

The possible links between postharvest flooding of rice fields and regional abundance of wintering waterfowl were assessed in five Western European landscapes. These areas were highly contrasted in terms of relative natural or semi-natural wetlands *versus* ricefield areas, and differed markedly in the proportion of rice fields being flooded. Such massive differences in overall habitats may have somewhat over-amplified the positive correlative relationship between flooded habitat cover and the number of counted ducks (**Article 2**). In other words, flooding a given previously dry ricefield region may not necessarily always induce an increase in duck numbers of the same order of magnitude than the differences we recorded between our Spanish, French and Italian regions. However, this correlation study was also backed up by the « experiment » caused by the introduction of the AES winter flooding in Spain, which effectively led to positive changes in long-term population trends. It is true that some of these new birds may have come from the Camargue, so that this latter site could maybe not be considered as a proper control when assessing trends in duck numbers, but once again the results were so clear and consistent that we are confident that winter flooding of rice fields does translate into higher duck numbers. We do not recognize the latitude as a factor explaining the small number of ducks wintering in the Italian study area rather than the lack of winter flooding, as there are major duck wintering sites at the same latitude (e.g. Venice Lagoon, Heath and Evans, 2000), and recent studies showed that in response to the increasingly mild winter conditions and hot summers, some wintering European duck species are shifting north-eastwards (Gunnarsson et al., 2012; Lehikoinen et al., 2013). The potential of improving the agricultural matrix for waterbirds in the Pô Plain through the introduction of ricefield winter flooding hence sounds realistic, and such new artificial wetlands would likely be readily used by ducks short-stopping (*sensu* Elmberg et al., 2014) along their flyway.

When trying to assess how habitat use by ducks could be modified by such possible changes in agricultural practices, through the empirical study of food resources in Camargue rice fields and nocturnal ducks counts, it was not possible to obtain a proper random sampling of the post-harvest practices in the 50 rice fields (**Article 3**). Indeed, most farmers did not accept to profoundly alter their practices for the project without financial support. We thus had to select farmers that already flooded their fields during winter, most of them doing so year after years for duck hunting purposes. Such stability in the practices may cause habituation of the birds to the use of some fields (wintering ducks can be very faithful to restricted geographic areas, e.g. Guillemain et al., 2010), which could be a different behaviour than if the rice fields where flooded for the first time and each farm was covered by a greater diversity of practices. However, admittedly the idea would be that winter flooding becomes a traditional practice in Camargue in the future, which **Article 2** showed could sustain greater wintering duck numbers in the long run.

The nocturnal surveys with the light amplifier presented in **Article 3** only provided information about duck numbers and ricefield use, but did not inform about habitat preferences or selection, since only rice fields were investigated. Further studies on food resource availability in other foraging habitats (natural wetlands as well as artificially baited

ones) and with radio tagged or gps-tagged birds would help to improve our understanding of duck movements and preferences for foraging habitats including rice fields, natural wetlands, wetlands managed for hunting etc...

It is true that such nocturnal counts could potentially be biased by imperfect estimation of bird numbers, double counts or imperfect detection. However, the rice fields are small (2.5 ha on average in the Camargue, Mouret, pers. comm.) and we counted birds once flying, which reduced our probability to miss ducks standing in the stubble. In any case the results were very explicit, since nocturnal duck density in flooded Camargue rice fields was among the highest ever recorded (our mean nocturnal density was 24 ducks/ha, when maximum historical averages ranged between 5 and 15 ducks/ha: Pirot, 1981; Mesléard et al., 1995), while dry fields were virtually devoid of any waterfowl during the night. Although the precision of the measurements could probably be improved (e.g. by correcting for detectability, Defos du Rau, 2003), the pattern is therefore very clear and established.

The two experimental tests were set up so as to isolate some of the processes related to agronomic benefits to farmers. Again the results were clear, with ducks in flooded fields bringing benefits in terms of straw disposal, but little effects of the birds or flooding itself in terms of depletion of the seed bank (**Articles 4 and 5**). Owing to the artificial situation of the experiments, these obviously had their own limits too. For example, the climatic conditions inside the greenhouse may have been different than in the proper fields, which may have caused different seed degradation rates (**Article 4**). The greenhouse experiment could also be extended in the future to consider seed germination and seedlings emergence after the flooding treatment, to properly assess the potential of winter flooding to organically control the weed plants during the next cultivation cycle, not just the viability of the weed seeds at the end of winter.

The test with the wing-clipped ducks also had to be conducted over a limited period of time for obvious constraints linked with the use of penned birds. We simulated the presence of a lower density of ducks during one whole winter by using many birds in a small enclosure over a short period of time. This prevented us from measuring straw decomposition over several months, but only stalk submersion (**Article 5**). However, in these two experimental papers the processes at play are clearly identified and the trends in the results are consistent and convincing. These studies hence already provide valuable results, which could be further improved by future complementary experiments.

IV.2 What could habitat management on rice production sites imply for duck conservation?

The dabbling ducks wintering in the rice field regions of Europe belong to several flyways or populations (depending on species, refer to delineations in Szabolcs et al., 2015). These populations do not currently cause major conservation concerns at the flyway scale and are all classified as “least concern” by the IUCN (2014) because their numbers are increasing (Gadwall, Teal, Mallard), stable (Wigeon, Shoveler) or fluctuating (Pintail) (Szabolcs et al., 2015). Anyway, these birds provide important cultural ecosystem services, in particular through their aesthetical value and through hunting (Mathevet, 2000). Although their population trends are generally positive, dabbling ducks are nevertheless among the waterbird species known to be particularly affected by changes in land use at the local scale, be these positive or negative (e.g., Duncan et al., 1999; Mathevet and Tamisier, 2002).

The Camargue is the most important winter quarter at the national scale for four of the six studied duck species (i.e., Mallard, Teal, Wigeon and Gadwall, Deceuninck et al., 2014), and hosts a significant proportion of the total French numbers: on average over the surveys 1965-2015 28% of the gadwalls, 26% of the shovelers, 21% of the wigeons, 20% of the teal, 10% of the pintails and 8% of the mallards (Deceuninck et al., 2014; A. Tamisier, M. Gauthier-Clerc and J.B. Mouronval unpublished data). It is also one of the most important winter quarters for dabbling ducks in general at the European flyway scale (Critical Site Network Tool, 2015). It is therefore relevant to assess how changes in Camargue habitat management may impact duck migration processes and population dynamics, both locally and at the flyway scale, especially when breeding and wintering habitat modifications, wetland disappearance or degradation are considered as the most important threats for these species (Cahiers Habitat Natura 2000, 2012).

The link between local land use changes and waterbird population trends at local and flyway scales have been established in two previous studies showing that waterbirds using rice fields show more positive population trends both in Spain (Rendón et al. 2008) and in Europe (Toral and Figuerola, 2010). The results of the **Article 2** also suggest that agriculture management could have an important impact on duck populations at both the local and the flyway scales.

Now considering that in Camargue: 1) availability of nocturnal foraging sites has been identified as a limiting factor for ducks (Brochet et al., 2009), 2) ducks are relatively faithful to their roosting sites across the winter (Guillemain et al., 2009; 2010) and fly short distances for feeding (Guillemain et al., 2008), and 3) many potential foraging grounds in harvested fields exist but are not used by ducks because they are kept dry during winter, we can safely hypothesize that ricefield winter flooding would immediately benefit to wintering ducks, which would start relying on these on a regular basis during the winter. Through greater wintering site attractiveness, we can hypothesize changes in residence time (Spanish Ebro Delta: Ferrer, 1986 versus Oltra et al., 2001; for Camargue Teal: **Guillemain et al., 2015a in Appendix I.2**), and changes in duck distribution (California duck wintering range shifted towards the Sacramento Valley when rice fields got flooded, Fleskes et al., 2005). All of this would imply that the provision of flooded rice fields would not only translate into a punctual or seasonal use by ducks during a given winter, but that strong wintering traditions could develop in these valuable habitats (see also **Guillemain et al., 2015a in Appendix I.2)**, hence translating into improvement of population dynamics rather than only the temporary satisfaction of bird energy needs. Indeed population trends actually increased after ricefield winter flooding AES implementation in the Spanish regions (**Article 2**).

We can hypothesize that a wide implementation of ricefield winter flooding in Camargue would influence duck movements and distribution locally, and have a positive effect more broadly on the duck populations. However, we largely ignore what would simultaneously happen in the other foraging habitats (shallow natural wetlands or hunting marshes) of the Camargue agricultural-wetland mosaic. Furthermore, at a larger scale, north-eastwards distribution shifting of wintering populations (Gunnarsson et al., 2012; Lehikoinen et al., 2013; Dalby, 2013; Elmberg et al., 2014) are currently occurring, largely due to favorable wintering conditions at higher latitudes. Changes in duck migration patterns at any given site result from both the changes in habitats of that area and those up and down the flyway (**Guillemain et al., 2015a; 2015b, Appendix I.2, I.3**). Considering that the Camargue is among the more southerly wintering sites in Europe, we ignore to what extent ricefield

winter flooding could potentially compensate for the consequences of climate change and birds increasingly staying in northern areas outside the breeding season.

Therefore, beyond an expected general improvement of the local habitat conditions for ducks, it is hard to predict from empirical and experimental studies such as those presented in this thesis what the consequences could be locally in terms of nocturnal duck distribution, and at the larger scale in terms of population dynamics. However, such studies like ours can provide valuable parameter values to feed modelling exercises. This is a project we have started to implement during this PhD, and plan to develop further in the near future.

The aim is to rely on predictive modelling to evaluate the likely consequences of alternative ricefield management in the Camargue -namely winter flooding at a large scale within the Camargue mosaic- on dabbling duck individual variables (*i.e.*, body condition, survival, habitat use and time budget). To reach this goal we set-up a collaboration with Professor John Eadie and his team at the University of Davis (California), who have been developing a powerful spatially-explicit agent-based model called SWAMP (Spatially-explicit Waterbird Agent-based Modeling Program: Miller et al., 2014). This model is relatively similar to the European MORPH model (Stillman, 2008). The most recent (so far unpublished) version of SWAMP is really adapted to our question as it allows the integration of agricultural landscape GIS and simulates the movements of ducks between daily roosting areas and nocturnal foraging patches. Furthermore, it is far more precise than energetic models (e.g. TRUEMET: Petrie et al., 2014), as it does consider heterogeneity in individual behaviour and body condition (allowing to run simulations with ducks having different lipid reserves).

SWAMP simulates the movements of a target community of ducks (**Forager list**) considering for each species their own diet (**Diet Type**) within a **landscape (vector GIS layer)** composed of **patches (Patch type)** of rice (dry, flooded, ploughed), moist soil wetland reserves (private, public) and maize *Zea mays* more or less forageable, considered as roosting, foraging or both habitats and including food items (gathered in a **Food list**) (see model flowchart on **Figure 9**). Each food is characterized by its own density, attack rate, handling time and decay (e.g. rice, maize, *Echinochloa crus-galli, Crypsis schoenoides, Polygonum spp.*). It is possible to add **Disturbance Events** (X times per hour) where ducks are flushed from the patch and fly to the closest patch but are not killed. The foragers enter progressively into the system across the winter, simulating gradual migration, and disperse to landscape foraging patches. They learn from each other and go foraging to the closer patch below a maximum duck density until reaching their lipid reserve needs or resource depletion reaches the giving-up density. Competition between foragers is indirect: depletion of food resources by one forager reduces the efficiency of subsequent foragers on that patch. After a simulation of one night, outputs are provided in terms of amount of energy remaining in the landscape, number of birds below their minimum lipid reserves and dying, total and average energy intake and demand of the duck community, use of each patch by the ducks and their time-budget, etc.

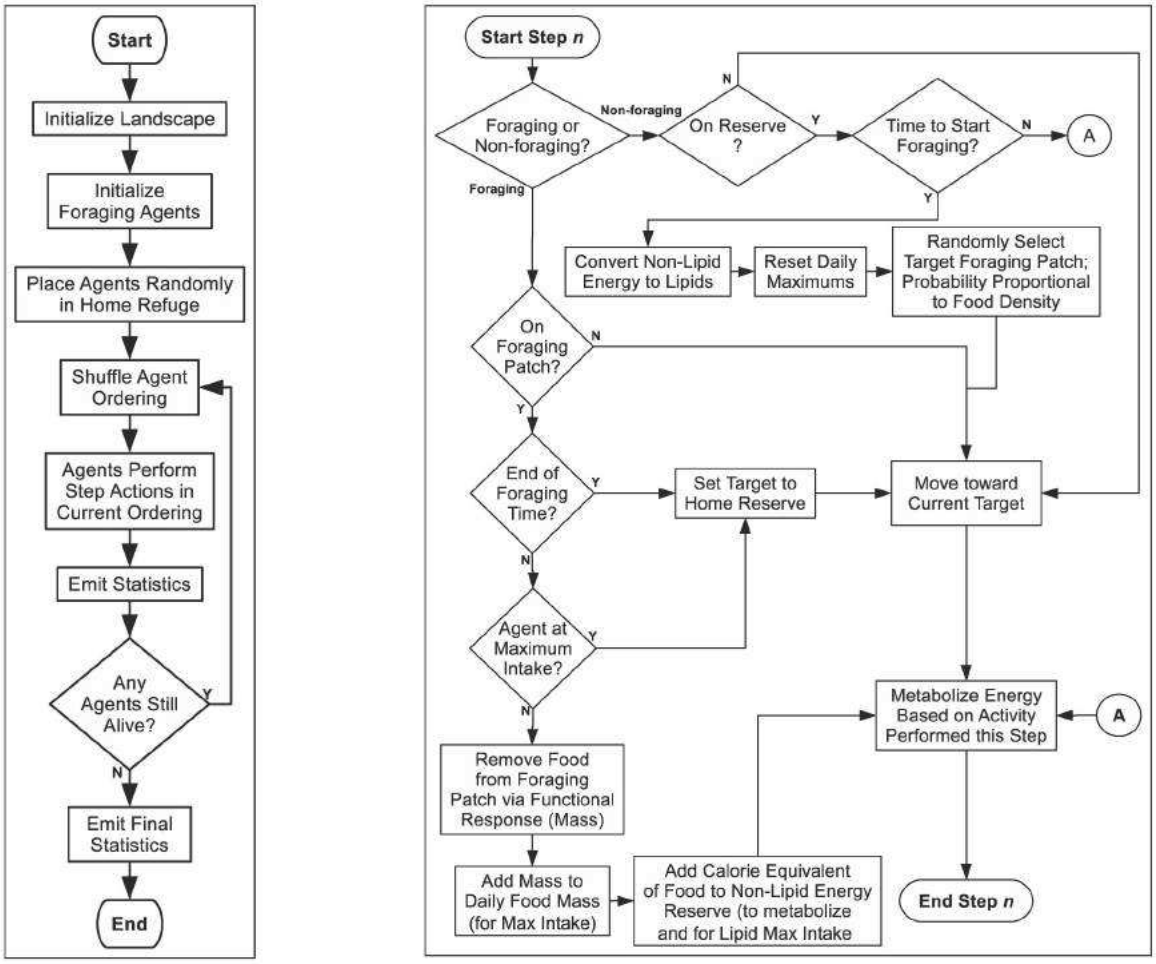

Figure 9. Forager flowcharts in SWAMP: main program loop flowchart (left) and agent step flowchart (right) (reproduced from Miller, 2014 with king permission from SAGE Publications).

A grant from the Doctoral School of the University of Montpellier allowed for a three-week internship with Professor Eadie and his team in California in February 2015. This period was spent learning about the model and its constituents, and determining the required changes for applying SWAMP to Camargue agricultural scenarios. During the internship we could run two preliminary simulations, one with Camargue rice fields flooded and one with only dry rice fields, which aimed at testing the integration of the GIS layer (relying on a land use study made in 2011 by the Camargue Natural Park, PNRC, 2013a) with defined roosting wetlands and rice fields and the real Camargue ducks numbers (average aerial counts per species per month 2000-2012), but without changing the species diet and food availability compared to the Californian settings. **Food items (**Tamisier and Dehorter, **Article 5**), **Food availability** (Tamisier and Dehorter, 1999, natural seed degradation : **Article 3, Article 5**), and **Diet Type** (for Teal and Mallard, Brochet et al., 2012) data are all available and will be considered in future model runs. We will validate that the model produces reasonable outputs using our food depletion data (**Article 3**), the data from our nocturnal surveys in rice fields (**Article 3**), and existing hunting bag data (J.-Y. Mondain-Monval unpublished data). However, modelling the movements of the wintering ducks between roosting and foraging sites in Camargue will demand some code modifications, to include seed consumption by other granivores (cranes that forage on dry rice fields, wildboars, rats, etc), hunting processes (baiting, disturbance, actual mortality of the ducks) and large-scale duck movements during

the winter (resident *versus* transient individuals, Guillemain et al., 2010). Finally there is relatively little information available on food availability in natural wetlands (Tamisier and Dehorter, 1999), so the sensitivity of the model to such parameters should be evaluated.

Miller et al. (2014) proved that SWAMP can be implemented to make predictions about duck conservation issues and help in management decision-making by testing different landscape change scenarios, hence helping current and future waterfowl management in California. Applying SWAMP in Camargue will allow similar projections to be made, and is among the next steps we plan to implement in the near future. Camargue farmers, stakeholders and decision makers are used to collaborate with scientists through joint modeling exercises (e.g. in the Tour du Valat Research Center: Mar Ô Sel software, http://www.mar-o-sel.net, Lefebvre et al., 2015). We believe that the provision of a powerful spatially-explicit agent-based model would greatly help rice farmers and land managers consider the consequences of rice field post-harvest management practices, and potentially changing for those we have demonstrated in this thesis as being the most beneficial to duck conservation.

IV.3 What could habitat management on rice production sites imply for rice farmers, for society and for decision makers?

For farmers, the main concern when deciding which field management to practice outside the cropping season is the cost of the various management options, so we concluded this PhD work by performing an economic evaluation of these as well as potential ecosystem services. The idea was to associate to our ecological results presented at length above an assessment of the economic balance of ricefield winter flooding.

We carried out a cost-benefit analysis to evaluate whether winter flooding in France would be economically realistic considering the constraints linked with flooding costs. In fact, contrary to the Spanish area where the Agri-Environmental Schemes “ricefield winter flooding” have been implemented, and where most of the flooding is done passively by gravity, in Camargue water must be actively pumped from the Rhône River and pumping costs constitute a main preoccupation for farmers that have multiple post-harvest options (**Article 6, Appendix 3**).

In addition to water pumping costs, this analysis was completed considering the market and non-market costs and benefits (i.e., agronomic and environmental benefits) of six different inter crop management sequences (post-harvest scenarios) including the use of different machinery in dry or flooded conditions (**Figure 10**). This analysis was carried out at both the individual farmer scale and a more macro societal scale. At the individual farmer scale, in addition to the costs of tillage operations and water pumping, waterfowl hunting and savings on pesticides or fertilizers though agronomic benefits were considered. At the macro societal scale, greenhouse gas emissions costs and ecosystem services such as landscape improvement with flooding generating cultural services (ecotourism, birdwatching) were considered.

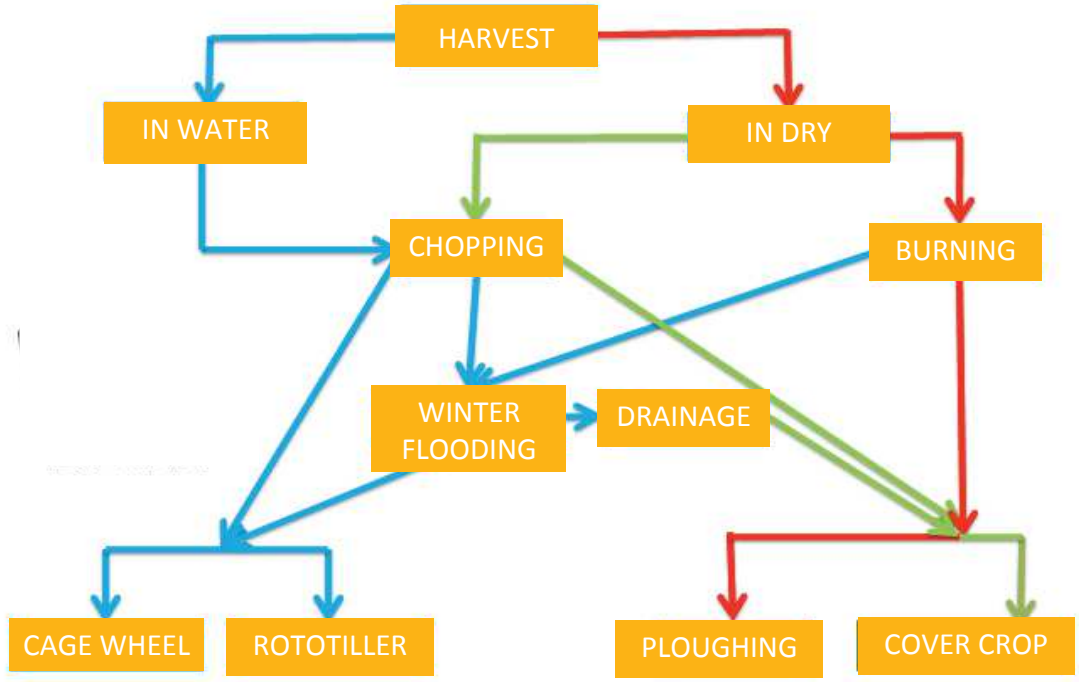

Figure 10. Post-harvest options in rice fields.

To briefly summarize the results, the current traditional and tolerated burning-ploughing practice barely reaches a financial equilibrium for the farmer (lowest benefits-to-costs ratio, although still above 1), and was associated with greater costs than benefits at the society level (benefits-to-costs ratio < 1). Such a practice hence seems no longer acceptable by society, largely because of greenhouse gas emission costs and the lack of ecosystem benefits that flooded fields can provide. The other scenarios were all economically realistic for both the farmer and society (benefits-to-costs ratios > 1). Harvesting rice in flooded fields was four times more profitable to farmers and more than eight times more profitable for the Camargue society than the traditional burning-ploughing (benefits-to-costs ratios for farmers: 4.15 *vs*. 1.02; for society: 6.67 *vs*. 0.78). The sensitivity analysis confirmed the robustness of the above results, since the ranking of the different scenarios generally remained the same even with very large (sometimes unrealistic) changes of the value of the cost or benefit estimates one by one.

The present results suggest that winter flooding in the Camargue is economically viable for individual farmers and is strongly beneficial for the macro society. Although the winter flooding scenarios are economically beneficial to farmers, there may still be some psychological hurdles to overcome (e.g. risk of accident associated with the use of cage-wheel tractors which may flip over). More information of the agricultural community about the possible indirect benefits brought by flooding may help the implementation of this technique. Providing financial incentives to farmers to flood the fields, like in Spain, may however be necessary to initiate winter flooding and allow them realizing the likely benefits of this practice. The benefits-to-costs ratios of winter flooding for society are so high that they would remain well above 1 even if a financial incentive was paid to farmers.

Economic valuation of ecosystem services has been advocated by a growing number of environmentalists as a short-term strategy to communicate the value of biodiversity in a language that reflects dominant political and economic views. It can provide complementary insights into sustainable ecosystem management and policy (Turner et al., 2000). However, the association of an economical value to ecological goods and services (direct market goods, non-market goods) is highly critical and should be taken with caution (Lant et al., 2008; Gomez-Baggethun and Ruiz-Pérez, 2011). The limits of such an evaluation in our study system have been discussed at the end of **Article 6 (Appendix I.1**).

For the real implementation of winter flooding at a large scale in Camargue rice fields, spatial analysis should be carried out to determine where in the delta it would be both easier and safer to flood and drain the rice fields. Depending on topography, Camargue farmlands are divided into "highlands" where altitude is greater than one meter, as opposed to "lowlands" (Monier et al., 2009). Rice is grown on the "highlands" in rotation with other cereals (wheat, maize, sorghum) and forage (alfalfa), and in monoculture on the salty, hydromorphic and difficult to drain "lowlands" (Mouret, 2013), where alternative crops are limited by soil salinity (Barbier and Mouret, 1992). In 2011, 8867 hectares (55%) of the cultivated fields of the Camargue Natural Regional Park were "highlands" and 7170 ha (44%) were "lowlands" (unpublished data extracted from land use study of Camargue in 2011, PNRC, 2013a). In the "lowlands", most farmers let water enter their fields from the irrigation network by simple gravity. In the "highlands", farmers must rely on an additional pump. Furthermore, catastrophic rainfall events are not infrequent (last flooding event in 2003) and if the Rhone River, the Vaccarès lagoon or the sea water levels are too high, it is not possible to drain the fields and the system is saturated with water. With climate change, such events may become more frequent. Assessment studies are currently carried out in the Camargue to improve the drainage systems owing to such potential risks of flood in the future (PNRC, 2013b). Potential implementation of rice field winter flooding in the area should be done while considering such water pumping constraints and risk assessments. Some ecological constraints may also potentially have to be considered in the future: in the Ebro Delta many rice fields have actually been kept dry or flooded with sea water over the recent years as a measure against the spread of the exotic apple snail *Pomacea insularum,* (Curcó and Bigas, 2014).

Economics and politics are the main driving factors of European rice production, which represents only 0.5% of the world production (FAOSTAT, 2012). The French production represents 4% of the European total, virtually all in Camargue. It has a low productivity and competitiveness due to relatively inappropriate climatic conditions and lowest access to pesticides compared to biggest and most powerful Spanish and Italian rice productions (C. Thomas, com. pers.). As a consequence, the French rice production is highly fluctuating depending on the national financial incentives and world market prices (**Figure 11**), which induce rapid changes in economic activity strategies of the Camargue properties and translate into fluctuating Camargue landscapes (Picon, 2008). After having been introduced in Camargue after the Second World War, replacing vineyards and a total of 40 000 ha of natural habitats (33 000 ha wetlands, Tamisier and Grillas, 1994), rice farming collapsed from about 32 000 ha in 1960 to only 4 000 ha by 1980. Support form the E.U. and improvement in the agricultural techniques allowed a recovery of the local rice-farming industry thereafter, which was associated with crop intensification, replacement of manual rice transplanting by mechanized sowing, hedges removal and increase of mean field area.

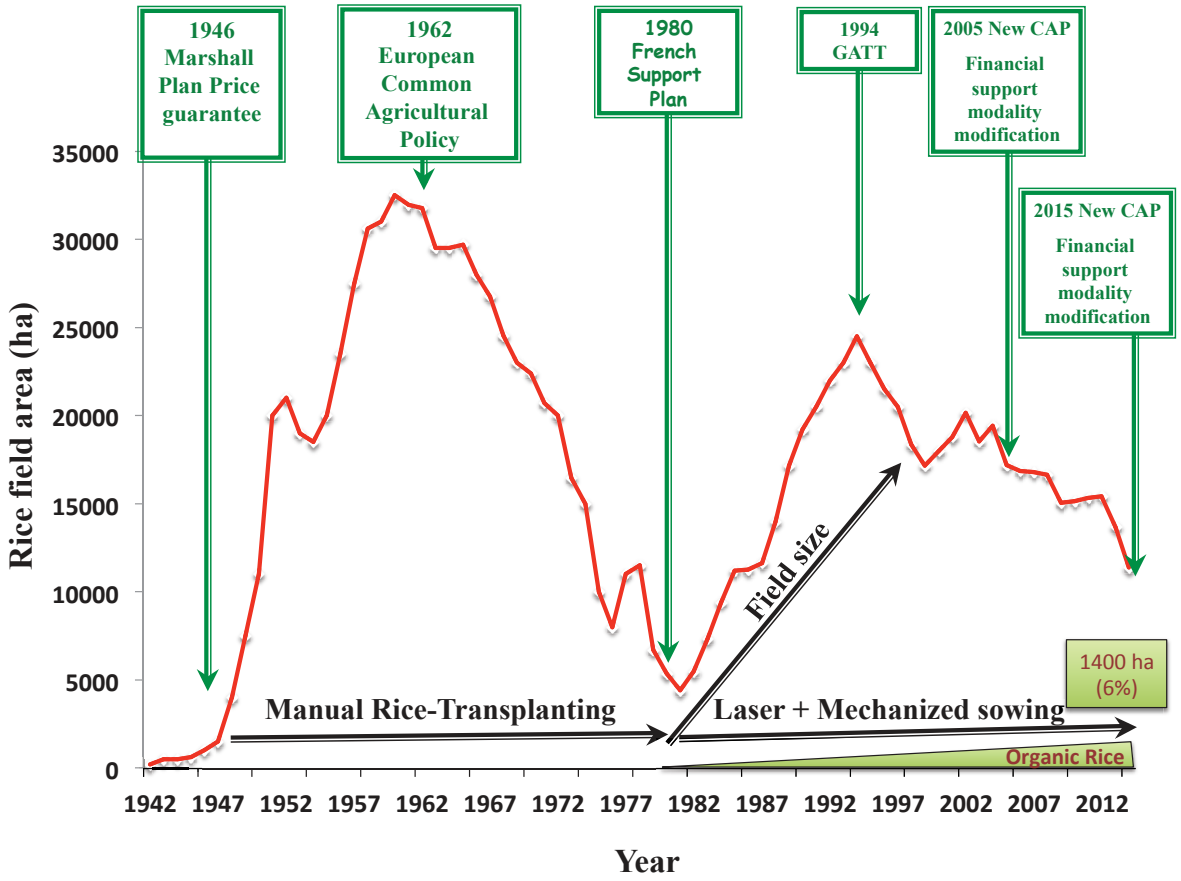

Figure 11. Changes in rice field cover in Camargue and agricultural practices: production is highly dependent upon the political and economical contexts (graphic built from unpublished data of J-C. Mouret, 2008 and France AgriMer, 2014).

Rice is currently the most widespread crop in the delta (61.5% of the crop in 2011, PNRC, 2013a). Recent changes in the European Common Agricultural Policy however already caused new changes in the landscape. Because the CAP 2015 plans suppress the specific financial support to the cultivation of rice (decoupling of the direct payments), changes in the Camargue crops have already been observed, with a ca. 28% reduction in rice area between 2012 and 2014, and replacement by dry crops such as wheat or vegetables, e.g., 1 200 ha of tomatoes (C. Thomas, unpublished data).

As part of the CAP 2015 reform, a series of Agri-Environment-Climate Schemes (AECS) associated with rice production and aiming to support environment and climate-friendly agricultural practices (e.g. mechanical false seed bed, dry sowing, laser surfacing, ban on straw burning) via financial incentives have been introduced to compensate for the average shortfall in earnings of c.a. 250 Euros/ha compared to the earlier situation (maximum contribution: 369 Euros/ha for two supplementary years of rice production). As a comparison, the promotion of ricefield winter flooding in the Spanish Ramsar sites was through a ca. 60 €/ha incentive through agri-environment schemes, an amount that would seem feasible in Camargue for the next CAP reform (**Article 2**). However, even in Spain the financial crisis and associated political decisions likely induced the end of the winter flooding incentive to rice farmers in Albufera de Valencia since 2012.

Flooding the rice fields may not be regarded as the absolute panacea, as this may be conflicting with concerns and programs on reduction of greenhouse gas emissions (European project tested in France, http://www.greenrice.eu/about-us/, http://www.sostrice.eu/en/ in Spain), except as an alternative to straw burning (Couderc, 2013). It may also counteract efforts to reduce water consumption (http://www.greenrice.eu/about-us/) or promote organic rice farming (Mouret, 2013), as winter flooding implies successive years of rice production (because autumn crops cannot be sown), while organic rice farming often relies on regular and rapid rotation with other crops. However, ricefield winter flooding is in conformity with, or complementary to, most of the concerns and management programs of the European and French rice production organizations: search for alternatives to rice straw burning (Monier et al., 2009 in France; ECORICE-Sustainable management of the rice straw LIFE04 ENV/ES/000184, Albufera de Valencia), reduction of pesticides (National Plan Ecophyto 2018 in France), reduction of soil salinity (rice tolerance to salinity, project France AgriMer, European project NEURICE). In this context, the current rice "crisis" calls for new research, and alternative management such as winter flooding may be supported for both the agronomic and environmental opportunities it could represent, hence opening the way for new income to rice farmers during a difficult period for them.

IV.4 CONCLUSION: What these results imply –and do not imply- for Camargue land management

This Phd work was focused exclusively on the dabbling duck community using rice fields and on the non-cropping period. We are aware that ducks do not constitute the whole bird community found among ricelands and that the sole post-harvest period does not evaluate the importance of rice production for birds in general (Tourenq, 2000; Toral, 2011). During the intercrop period, rice fields have also been shown to be important for other waterbirds such as Black Godwit *Limosa limosa (*Lourenço and Piersma, 2008; Lourenço et al., 2010), Snipe *Gallinago gallinago* (Beck et al., 1999), White Stork *Ciconia ciconia*, Eurasian Spoonbill *Platalea leucorodia* (Marti and del Moral, 2003) etc, which may not necessary be favoured by the same water levels or post-harvest practices (Toral et al., 2011). While positive for ducks, flooding of rice fields in winter may hence potentially have negative consequences for other birds (Elphick, 2004). In fact, dry rice fields also constitute a suitable habitat for other birds (e.g. raptors, passerines, Elphick, 2004). Wintering crane (*Grus grus*) numbers have been increasing quickly in the dry rice fields of Camargue over the very last years. We actually performed diurnal and nocturnal surveys of the waterbird community in the rice production area of Doñana in the delta of Guadalquivir in November 2014. Fields with different straw and water management were covered, allowing a broader reflection on the consequences of post-harvest practices for the entire avifauna community, not just waterfowl. These data are still being analysed.

Earlier research in the Camargue, which was conducted across the whole year but limited to diurnal surveys, concluded that bird diversity was lower in rice fields (31 species) than in natural marshes (59 species) (Tourenq et al., 2001). Our results actually show that natural wetlands and flooded rice fields (acting as semi-natural wetlands) are complementary. We do not ignore that winter flooding, although beneficial to ducks, is not necessary the best option for biodiversity in general (Tamisier and Grillas, 1994, see also above). Our aim here was to re-establish the function of duck foraging habitat by appropriate management of harvested rice fields, which could be used by the birds in parallel to more natural habitats. It is also important to note that we are not advocating the conversion of natural marshland into rice

fields, only a change in the management of existing fields to make these accessible to foraging ducks.

The mutually beneficial option that winter flooding could represent for waterfowl and farmers opens the dialogue and research collaboration between ecologists and agronomists. Agronomists have started to work on new farming strategies in Camargue (e.g., Jaek, 2010; Delmotte, 2010). These studies however mostly consider the promotion of organic farming in the Camargue. Conversely, how to improve the currently dominant conventional rice farming by integrating agronomical and ecological approaches has received very limited attention so far. The wide introduction of winter flooding could be a strategic way to gain the best from recent knowledge obtained in these two disciplines. In the context of the current rice production problems, actually causing a decline in Camargue rice area, winter flooding may also open the way for new income to rice farmers and contribute to overcome the crisis.

Changes in the Common Agriculture Policy have recently caused the reduction of Camargue ricefield area by one third, inducing two major changes in the landscape: the increase of fallow and the development of dry crops. Some increase in fallow area had already been noticed in the 2011 Camargue land use study (PNRC, 2013a), and is expected to keep on expanding, mostly on salty low altitude lands. These areas may represent a good opportunity for wetland restoration plans. In fact, as for the rice production area of Doñana in the delta of Guadalquivir, the restoration of former rice fields into marsh areas (Mesléard et al., 1995; Muller, 2013) could complement the maintenance of rice cultivation flooded during winter in other areas. This would seem a more environmentally friendly strategy than the transformation of these abandoned rice fields into cotton (Doñana), tomato fields (Camargue), or solar farms (Toral, 2011).

At the beginning of this PhD, we wondered if sustainable intensification could be possible within European rice fields. We were able to demonstrate that 'win–win' agricultural scenarios for rice producers and waterfowl conservation are possible within these intensive production areas, especially in France. The last step of the adaptive conceptual framework is then to share the results to facilitate learning. Such communication is necessary to bridge the gap between researchers, land managers (including farmers) and decision makers, to confront common and different visions of the landscape (Vuillot, 2015), and to ease practical implementation. This is what we have initiated with key Camargue and European audiences (**Appendix III**). The results have been well received by farmers, hunters, and conservation managers alike. Due to the iterative nature of the adaptive management cycle, this final "learning" step is also often an important input for the next steps of the project cycle. We hope that the results of this PhD will contribute to increase the conservation value of rice fields while maintaining the economic viability of productive agriculture.

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APPENDICES

I. ADDITIONAL PAPERS

APPENDIX I.1

Article 6:

A cost-benefit analysis of ricefield winter flooding for conservation purposes in Camargue, Southern France

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Submitted in *Agriculture, Ecosystems and Environment*

Abstract

Rice plants have high silica contents, preventing most of the uses generally made with straw from other crops. The most common practice is thus to burn rice straw after harvest then plough the fields. Flooding these during winter may be a good alternative yielding both agronomical and environmental advantages, but whether this is economically profitable has never been properly assessed. A cost-benefit analysis was hence carried out to confront six possible agricultural scenarios during the rice intercrop period, separately at the scale of the single farmer and at the society level. All scenarios were economically realistic (benefits-to-costs ratios > 1 for the farmer), but the most beneficial appeared to be harvesting rice in flooded fields, which saved the irrigation pumping costs. Similar results were found at the society level, except that burning-ploughing was no longer acceptable (benefits-to-costs ratio < 1), largely because of greenhouse gas emissions costs and the lack of ecosystem benefits that flooded fields can provide. Again, harvesting rice in flooded conditions and keeping the water in the fields afterwards was the most profitable option, and remained so throughout the range of simulations carried out as part of a sensitivity analysis. Because it facilitates straw and weed seed decomposition, and also brings a range of environmental benefits, including the provision of extensive foraging habitat to wintering waterfowl, flooding the harvested rice fields instead of burning and ploughing these should be promoted. The present study suggests this is economically realistic for farmers, and strongly desirable for society.

Keywords: Cost–benefit analysis; Flooding; Ricefield; Winter management; Waterfowl.

1. Introduction

Rice cultivation is associated with a range of constraints for farmers. First, the flooding of the ricefield during growth creates favorable conditions for a range of weeds, some of which are pioneer species in temporary wetland ecosystems, meaning that they are very fast-growing and successful in seasonally flooded habitats (e.g. *Cyperaceae*, Baki et al., 2000; Oerke, 2006; Anders et al., 2008; Rodenburg and Johnson, 2009). Rapid colonization by weeds often limits the quantity of successive years of rice cultivation. As a result, farmers must come to a compromise between regular crop rotation or the heavy use of herbicides, hence largely being prevented from switching to organic farming (Palvadeau et al., 2012). Another problem that rice farmers face is the high silica content of rice straw, limiting the use as a compostable bi-product (e.g. wheat straw used as litter for livestock) and requiring farmers to dispose of rice straw without any foreseeable benefit. The simplest method for rice straw disposal is burning, which has long been and is still practiced in many areas (Monier et al., 2009). However, greenhouse gas emissions, air pollution issues caused by fine particles and other problems linked with smoke created by burning fields have led to the ban of this technique in some areas (e.g., California Rice Straw Burning Act 1991 in Anders et al., 2008), calling for alternative practices.

One alternative practice is to flood the rice fields after harvest. This has proven an efficient means of promoting straw decomposition (review in Pernollet et al., 2015a). Furthermore, some weed seeds have also been shown to loose mass or viability more rapidly in flooded conditions, thereby potentially reducing the need for herbicides (Manley et al., 2005; Fogliatto et al., 2010). Flooding rice fields after harvest also creates vast areas of shallow wetlands. These are artificial habitats, yet they provide very attractive grounds for a large number of wintering waterbirds (Eadie et al., 2008; Pernollet et al., 2015b). The birds could provide additional benefits by themselves further promoting the decomposition of straw by trampling and dabbling (Bird et al., 2000; Brogi et al., 2015) and the consumption of some weed seeds (van Groenigen et al., 2003, see however Brogi et al., 2015). Summarizing all the above, a recent literature review concluded that the promotion of winter flooding in harvested rice fields would be a win-win strategy by which farmers could support wildlife conservation while also gaining agronomic and other ecosystem service benefits (Pernollet et al., 2015a). A preliminary approach considering potential savings on direct costs suggested winter flooding would be economically beneficial (Manley et al., 1999; 2005), but to date a thorough economic evaluation of winter flooding considering all costs of field flooding, tillage operations, savings on nitrogen and pesticides costs, financial incentives or income from hunting, ecotourism or other ecosystem services still had to be carried out and was greatly required (Manley, 2008).

Flooding rice fields during winter may be costly because of the energy required to pump the water. To overcome these costs, subsidies are often given to farmers who undertake winter flooding (e.g. in California, The Nature Conservancy, 2014; in Spain, Pernollet et al., 2015b). In France rice is primarily grown in the Camargue, a vast delta created by the two branches of the Rhône River. Compared to other major waterbird winter quarters in Europe, the Camargue still has extensive areas of natural wetlands. To date only 9% of the Camargue rice fields are flooded in winter compared to 62% in the Ebro delta and Albufera de Valencia, Spain. The post-harvest flooding in the Camargue is mostly for hunting purposes and Camargue farmers receive no financial incentives for flooding (Pernollet et al., 2015b). This may restrict the development of winter flooding of the Camargue rice fields, which is further limited by the fact that Camargue farmers have to pay pumping costs while in other areas (e.g. the Ebro

Delta) the fields can be flooded simply by gravity. Therefore the most common practice in the Camargue remains the rapid burning of the straw after harvest, followed by ploughing of the dry fields during winter (75% of the residual rice straw still undergoes burning in Camargue, the remaining 25% mostly being chopped, Monier et al., 2009). Despite the agronomic and environmental benefits potentially brought by post-harvest flooding of rice fields, this will only be implemented by farmers if it is financially acceptable. The aim of the present paper was therefore to conduct a proper cost-benefit analysis of ricefield winter flooding to determine whether this would be an economically feasible option for French rice farmers. We also compared the benefits-to-costs ratio with alternative farming practices during the non-growing season, including the current burning-ploughing practices (Monier et al., 2009). Beyond the individual farm, we analysed the potential costs and possible benefits to society, so as to discuss whether financially supporting Camargue rice farmers with public funds to flood their fields during winter would be appropriate.

2. Methods

2.1. Study area

The Camargue delta (43°30'N, 04°30'E) covers about 145,000 ha, of which ca. 15,000 ha are currently cultivated in rice (Parc Naturel Régional de Camargue hereafter PNRC, 2013a). Water is pumped from the Rhône River and subsequent provision is through a network of canals and channels maintained by specific local organisations (Associations Syndicales Autorisées – ASAs). All farmers pay the ASA for irrigation rights except the farmers located along the river who may use private pumps directly from the Rhône. Farmers that want to flood on the more elevated lands (hereafter high lands, above 1m high, 55% of the total agricultural area) have to use an additional private pump, either a tractor-held pump or private electrical pumps. The fields are most generally dried out during the end of summer to allow harvest in late September or early October, using a drainage network also ran by ASAs. Given that organic farming comprises less than 6% of the cultivated land (Palvadeau et al., 2012), our analysis was restricted to conventional farms only. Furthermore, the straw management options are similar in organic and conventional farming.

2.2. Economic evaluation

We relied on a cost-benefit analysis (CBA), which is based on the economic efficiency criterion, simply measuring whether the total benefits of a particular action are larger than the total costs (Hanley, 2009). Such analyses are becoming increasingly popular with policy-makers and have been applied in the context of conservation justification (Turner et al., 2000), conservation controversy (MacMillan et al., 2004) or in environmental impact assessment such as energy projects (Snyder and Kaiser, 2009).

We used benefits-to-costs ratios of various selected farming scenarios outside the rice growing season. Compared to alternative approaches such as cost-efficiency analysis or multicriteria analysis, the CBA has the advantage of considering costs and benefits in the same monetary unit (Pearce et al., 2006).

We first held key informant interviews with agricultural engineers and farmers to identify the most common practices used by Camargue rice farmers to manage their fields from harvest to the beginning of the next growing season. We also identified the most likely alternatives for field use after rice harvest, including winter flooding. For each scenario we listed all potential costs and benefits, separating those experienced by the individual farmer and those for society

as a whole (including the farmer, to get a comprehensive balance). For each cost or benefit, we obtained quantitative estimators (expressed in €/ha) from literature searches and data collection from the key informants. The geographic scale of analysis covered the total 11,390 ha of Camargue rice fields within the Camargue Natural Park in 2014 (France AgriMer, unpublished data), and the temporal scale of analysis was limited to the period from harvest to straw incorporation into the soil. All costs and benefits considered hence pertain to one single cultivation cycle and values were adjusted by taking inflation rates into account from the year they were collected to year 2014 (INSEE, 2014: www.insee.fr). A simple ratio of benefits on costs was then computed to evaluate each scenario compared to the current burning-ploughing practice, and a sensitivity analysis was conducted to evaluate the extent to which changes in the parameters would potentially change such evaluation, at the individual farmer and the societal scales (for more methodological details and limits of cost-benefit analysis, refer to Hanley et al., 2009).

2.3. Agricultural scenarios

A total of six inter crop management sequences, called scenarios hereafter, were considered in the analysis, combining the various options available to farmers at each stage from harvest to the end of the winter (Table 1).

In addition to winter flooding we tested only the most common current practices. Harvest was included because whether it is done on dry fields (as most often is the case) or in fields still flooded (practiced only in a few Camargue farms, but largely used in Spain) will profoundly affect the subsequent operations and costs. Straw can either be chopped during harvest, with the addition of a crusher onto the combine harvester itself, or concentrated as swath by the harvester and later burnt. Fields dry at harvest may or may not be subsequently flooded, then potentially drained again. The soil may either be worked deeply (ploughing, only in dry fields) or more superficially (using a cover-crop in dry fields, cage-wheels or rototiller in flooded fields). For each of these sets of practices we then listed the costs and benefits. This encompassed market costs and benefits (those directly costing or bringing money to the farmer, including lost opportunity costs and avoided costs) as well as non-market ones (e.g. environmental damages, ecosystem services, also relevant to society) (see appendices 1 and 2 for full details). Some costs or benefits were not included in the present analysis (indicated by a star in the two appendices). In some cases this was because no quantitative estimate could be found (e.g. yield loss of the cumulated effect of crop lodging and harvest in flooded condition, future costs associated with the degradation of soil structure by ploughing, benefits provided by straw burning in terms of reduction of weeds and rice diseases). Some other items were considered negligible at the present time (risk of overexploitation of water resources, given that water comes from pumping in a very large river very close to its mouth, catastrophic floods due to heavy rains associated with flooded rice fields, given the effective drainage network provided by the ASAs), but could be necessary to consider in the future. Finally, some costs or risks were considered highly unlikely, especially since the analysis was carried out at the scale of one single cultivation year. These elements included the risk of fire associated with the burning of straw and the accident risk to farmers associated with the use of cage-wheel tractors, which may occasionally flip over.

Table 1 The six possible scenarios considered in the cost-benefit analysis for the Camargue.

No.	Harvest	Straw disposal	Flooding	Straw incorporation
1	Dry fields	Burnt	No	Ploughing
2	Dry fields	Chopped at harvest	No	Cover-crop
3	Dry fields	Burnt	Winter pumping	Cage-wheels
4	Dry fields	Chopped at harvest	Winter pumping + drainage	Ploughing
5	Dry fields	Chopped at harvest	Winter pumping + drainage	Rototiller
6	Flooded fields	Chopped at harvest	Water from pre-harvest+ drainage	Rototiller

2.4. Costs and benefits for the famer and for society

2.4.1. Market costs: salary, fuel and fixed costs for the farmer

The costs for salary and fuel were calculated using data provided by the INRA Montpellier UMR Innovation database, which is largely based on Delmotte (2011), and fixed costs for each practice were calculated using information provided by the Bureau de Coordination du Machinisme Agricole (Pérès et al., 2014). The latter include the machinery insurance and storage costs as well as the depreciation rate of the machinery. Note that such fixed costs were not available for cage-wheels and private pumps, and were hence not considered here. Fixed costs included 500 hours of use per ha per year for tractors and a minimum of 200 hours per ha per year for the other equipment (Pérès et al., 2014). Because tractors may be used for other activities during other parts of the year than our study period (e.g. to sow rice or spread fertilizers during spring) the value used here may be slightly overestimated since we were only interested in the harvest+intercrop period, but the bias should be relatively similar among all scenarios considered here. The values of salary, fuel and fixed costs for each scenario are provided in Table 2.

Table 2 Basic market costs to farmers under the various agricultural scenarios (the numbers in parentheses correspond to the activities in Table 1). Values provided in Euros per hectare during the post-harvest period (October through February), computed from Delmotte (2011) and Pérès et al. (2014) for the salary, fuel and fixed costs with correction for inflation. Costs for high lands were used for benefits-to-costs ratios calculation.

Scenarios	Salary costs	Fuel costs	Irrigation and drainage costs		Fixed costs		Total costs	
			Low lands	High lands	Low lands	High lands	Low lands	High lands
Burning – ploughing (1)	30.39	51.97	-	-	82.77	82.77	165.13	165.13
Chopping – cover-crop (2)	25.18	39.13	-	-	84.45	84.45	148.76	148.76
Burning – flooding – cage-wheels – drainage (3)	39.69	37.63	129.69	161.32	67.8	109.05	274.81	347.69
Chopping – flooding – drainage – ploughing (4)	34.49	58.18	129.69	161.32	96.17	137.42	318.53	391.41
Chopping – flooding – rototiller – drainage (5)	30.98	43.83	129.69	161.32	89.95	131.2	294.45	367.33
Harvest in water – chopping – rototiller – drainage (6)	30.98	43.83	18.22	18.22	100.03	100.03	193.06	193.06

2.4.2. Market costs: irrigation and drainage costs for the farmer

As explained above, irrigation and drainage services and maintenance in the Camargue are provided to rice farmers through a collective system managed by the ASAs. All owners of land within the area of a given ASA have to pay a basic annual fee called "ordinary cost" to contribute to the running of the system (the fees are divided into irrigation and drainage costs as they might not concern the same ASA). Farmers using water to flood their fields pay a second fee termed "exploitation fee". This value depends on the number of hectares to be flooded and the crop to be grown (based on the water needs for each crop). Each ASA determines its own basic and exploitation fees. There are a total of 22 ASAs in the territory of the Camargue Natural Park. Because rice fields are currently flooded mostly during the rice growing period (spring and summer), there is no established value for the cost of winter flooding. This may theoretically be greater given the higher cost of electricity during winter

(as prices generally change in November), but farmers may also benefit from cheaper "summer" prices if they were flooding their fields right after harvest (during early October). The analysis was hence conducted using current summer prices, but simulations were made during the sensibility analysis to evaluate the performance of scenarios with field flooding at increased winter pricing. Farmers pay per hectare to be flooded, not per water depth, i.e. volume of water to be pumped. In all simulations, we considered that farmers would pump water only once, after harvest, and would then close the water gates to keep the water in the fields until February. This pumped water would be combined with winter rains (average 58.0 mm across winter, PNRC, 2013b). We used the mean exploitation fees for irrigation (considering that the ordinary role for irrigation is already paid for the previous rice growing period), and the mean ordinary drainage fee over all Camargue ASAs, yielding an average cost of 111.47 €/ha for irrigation and 18.22 €/ha for drainage (raw data, ASAs, unpublished data). In the low lands, most farmers let water enter their fields from the ASA network by simple gravity. In the high lands, farmers must use an additional private pump. Considering this is mostly done using a tractor-held pump (electrical pumps also exist, but the cost of their use was unknown) with a 1800 m^3/h debit held by a 90 hp tractor using 6 litres of fuel per hour and the need to pump 10,000 m^3/ha (yielding a ca. 10cm water depth, the ideal depth for foraging ducks), on high lands farmers would pay an additional 24.97 €/ha to flood their fields. Farmers harvesting flooded fields were considered to be able to retain water from the cultivation phase in their fields during the next winter, i.e. would pay no irrigation costs, only the drainage ordinary cost. All scenarios including some degree of flooding include basic drainage fees. The irrigation and drainage costs of each scenario are given in Table 2, separated according to low and high lands. For computing the benefits-to-costs ratios we only considered the high lands and a systematic use of winter drainage, so as not to artificially favour the flooded scenarios by the cheaper irrigation costs of low lands.

2.4.3. Lost opportunity costs for the farmer: fertilization to compensate for nutrient losses to fire

Rice produces ca. 6 tons of dry vegetal matter per ha (seeds excluded), of which 5.1 tons are cut straw, and 0.9 tons (15%) are stalks and roots (Mouret et al., 2010). Burning one ton of cut cereal straw leads to the loss of 6 nitrogen units, 2 phosphorus units and 12 potash units, corresponding to 12.9 € of fertilizers to be added for compensation (Peloquin, 2010). Burning the 5.1 tons of straw cut per hectare instead of crushing and incorporating it into the soil would hence force farmers to spend an additional 69.41 €/ha on fertilizers (inflation included).

2.4.4. Non-market costs: Greenhouse Gas Emission costs for the society

The only non-market *costs* which were considered regular enough to be included into the analysis (see above) were those linked with Greenhouse Gas (GHG) emissions. We considered GHG in the form of CO_2, CH_4 and N_2O linked with fuel combustion by machinery use, straw burning, and soil emissions caused by incorporation of straw and flooding of the rice fields. Because they were unknown, we did not consider GHG emissions resulting from energy used by irrigation and drainage pumps of the ASAs (note that many of these are electric). Emissions linked with production, transport, storage and use of fertilizers and pesticides are known to be a major source of GHG emission in agriculture (e.g. Couderc, 2013), but were not considered here as these are used during the rice growing period. We first quantified soil emissions of CO_2, CH_4 and N_2O. We calculated the global warming impact based on CO_2 equivalencies of CH_4 and N_2O using the ratios provided by the Intergovernmental Panel on Climate Change (IPCC, 2006), i.e. 25 tons equivalent CO_2 for 1

ton CH_4 and 298 tons CO_2 for 1 ton N_2O. The economic value of such emissions was then estimated, considering a 7 € cost per ton of CO_2 as implemented by the French Ministry of Economy and Finances (2014).

Table 3 shows the greenhouse gas emissions caused by fuel use of each specific machinery for the work carried out on one hectare of rice fields. GHG emissions from straw burning were taken from Couderc (2013) for conventional rice farming: 9,313 kg CO_2/ha, 16.6 kg CH_4/ha and 0.43 kg N_2O/ha, which represents a total equivalent to 9.9 tons of CO_2/ha.
Some N_2O is emitted by the soil following nitrification-denitrification of the dry organic matter if it is incorporated. Considering that rice cultivation produces 6 tons of dry organic matter per hectare (see above), 85% of such matter may be incorporated when a plough, cover crop, rototiller or wheel cages are used after chopping (i.e. not burning) straw (Doublet, 2011), rice crop residuals contain 0.7% nitrogen (Doublet, 2011), 1% of such nitrogen would be emitted by soils as N-N_2O (IPCC, 2006) and the correction factor from N-N_2O to N_2O is 44/28 (Doublet, 2011), 0.00066 tons N_2O would be emitted by soils per ha, corresponding to an equivalent of 0.197 tons CO_2 if all stalks, roots and straw were incorporated to the soil. When the straw is burnt and only stalks and roots are incorporated, this value would fall to 0.00011 tons N_2O emitted by soils per ha, corresponding to an equivalent of 0.033 tons of CO_2.

Finally, some CH_4 is also emitted by ricefield soils, especially if flooded, corresponding to 3 kg/ha/day after Roger et al. (1999). This is equivalent to 360 kg CH_4 or equivalent 9 tons of CO_2 over the 120 days of the study period. To summarize, Table 4 shows the total greenhouse gas emissions and their cost value for society under each of the 6 agricultural scenarios.

Table 3 Greenhouse gas emissions associated with the use of each tool during the harvest and post-harvest periods.

Machinery	Fuel consumption (l/ha) [3]	CO_2 emission (kg/ha) [4]	CH_4 emission (kg/ha) [4]	N_2O emission (kg/ha) [4]	Equivalent CO_2 (t/ha)
Combined harvester [1]	24	64.08	0.00364	0.00127	0.064
Crusher [2]	7	18.69	0.00106	0.000371	0.019
Cover-crop	11	29.37	0.00167	0.000583	0.029
Plough	31.25	83.43	0.00475	0.00165	0.084
Cage-wheels	16	42.72	0.00243	0.000848	0.043
Rototiller	16	42.72	0.00243	0.000848	0.043
Private irrigation pump	33.3	88.91	0.00506	0.00176	0.089

[1] Fuel use considered equivalent for combined harvester used in flooded and dry fields.
[2] Additional fuel use when a crusher is fixed to the back of the combined harvester.
[3] From Delmotte (2011)
[4] using 2.67kg CO_2, 0.000153kg CH_4 and 0.0000532kg N_2O per litre of fuel burnt (van Kempen, 2010; EnviroConsult, 2011)

Table 4 Greenhouse gas emissions under the six agricultural scenarios (the numbers in parentheses correspond to the activities in Table 1) and their equivalent cost to society (see text for details of the calculations).

Scenarios	CO_2 emission (kg/ha)	CH_4 emission (kg/ha)	N_2O emission (kg/ha)	Equivalent CO_2 (t/ha)	Societal cost (€/ha)
Burning – ploughing (1)	9460.51	16.60	0.54	10	70
Chopping – cover-crop (2)	112.14	0.0063	0.66	0.31	2.17
Burning – flooding – cage-wheels – drainage (3)	9508.71	376.60	0.54	19.10	133.70
Chopping – flooding – drainage – ploughing (4)	255.11	360	0.67	9.45	66.15
Chopping – flooding – rototiller – drainage (5)	214.40	360	0.66	9.41	65.87
Harvest in water – chopping – rototiller – drainage (6)	125.49	360	0.66	9.32	65.24

2.4.5. Avoided costs: reduced need for fertilizers and herbicides for the farmer

The first set of potential benefits for the farmer is avoided costs, i.e. saved expenses owing to the use of alternative methods. The first of these avoided costs relates to dry organic matter incorporation (either by ploughing, use of cover-crops, rototilling or use of cage wheels). This follows an inverse reasoning compared to losses due to burning the straw described above. Incorporating one ton of rice straw or stalks corresponds to a saving 12.9 € per ha on fertilizers (Peloquin, 2010). As we have previously mentioned, one hectare of rice produces ca. 6 tons of dry matter (Mouret et al., 2010). When straw is burnt only the stalks can be incorporated, reducing dry matter inputs. Considering that this represents approximately 15% of the total dry matter, only one ton of dry matter is incorporated when the fields are burnt. With a 5.5% cumulated inflation rate from 2010, incorporating the residual dry matter from a burnt field (i.e., only stalks and roots) brings a 13.61 € saving per ha. When straw is chopped instead of burnt the entire 6 tons of dry matter can be incorporated, equating to 81.66 € saved on fertilizer costs per hectare.

The second set of potential savings is related to herbicides: first, flooding rice fields during winter is known to reduce some of these weeds, in particular weedy rice (*Oryza sativa* var.) whose viability is reduced by up to 95% (Fogliatto et al., 2010). Using the guide on weed

limitation prepared by the French Rice Organisation (Centre Français du Riz, CFR, 2011), corrected with a 3.4% cumulated inflation rate from 2011 to 2014, 95% reduction of weedy rice seed stocks would correspond to a savings of 52.90 € per hectare (including the costs associated with the purchase and application of herbicides). Secondly, when farmers can grow several types of crops in their field, crop rotation between rice and wheat (or alfalfa when possible) also constitutes an efficient means of controlling weeds (e.g. Hammond et al., 2012). In our case crop rotation was assumed to be possible only and implemented always following the dry scenarios 1 and 2. According to CFR (2011), such crop rotation would impact a wider range of weeds than only weedy rice, corresponding to a savings of 225 € on herbicides per ha.

2.4.6. Market benefits: Agri-environmental schemes for the farmer

The French government and the European Union jointly support environment and climate-friendly agricultural practices via financial incentives called Agri-Environment-Climate Schemes, contracted by farmers and implemented through the Common Agricultural Policy (CAP) (EC Directorate General for Agriculture and Rural Development, 2005). Here we only considered the two such incentives of the last CAP revision that can be received by rice farmers for practices implemented outside the crop-growing season. Measure "Couver16" supports the incorporation of rice straw (owing to the likely benefits in terms of reduced need for fertilizers and absence of air pollution with straw combustion). This measure is contracted for a three-year time period. Measure "Irrig09" is contracted for two additional years of rice cultivation and supports flooded crops (rice). In our study, all scenarios with winter flooding (which impose a subsequent flooded crop owing to the inability to implant a dry crop such as winter wheat), i.e. scenarios 3-6, were considered to receive a 44.76 € incentive per hectare with measure "Irrig09". All scenarios where straw is chopped and later incorporated (2, 4, 5 and 6) were considered eligible to "Couver 16", i.e. would receive 180.74 €/ha. Scenarios where straw is chopped and incorporated, in fields that are also flooded (i.e. scenarios 4-6), were considered to receive 225.50 €/ha as they combine the benefits from both measures. The most common practice,burning-ploughing (scenario 1) is the only scenario that is not entitled to any Agri-Environment-Climate Schemes.

2.4.7. Hunting in rice fields: market benefits and provisioning + cultural ecosystem services for farmers

Tamisier and Dehorter (1999) estimated that a minimum of 100,000 ducks are shot annually by hunters in the Camargue on a total area of 27,000 ha, hence an average of 3.7 ducks/ha/year. Flooded rice fields are among the habitats where such wildfowling activity occurs (e.g., Tamisier and Dehorter, 1999; Mathevet, 2000). Considering a market cost of 5.85 € per Mallard (*Anas platarhynchos*) in 2014 (Au gibier de France website, http://www.gibierdefrance.com/tarifs-gibier/colvert/, accessed on May 2015), the most commonly hunted duck, hunting would represent an ecosystem provisioning service corresponding to 21.65 €/ha on avoided food costs.

The enjoyment obtained by hunters from wildfowling over flooded rice fields also represents a (non-market) benefit to society and so to the farmer as an own lobby. This was evaluated at 46.65 €/ha by Calvet et al. (2011), (corrected for inflation to 2014), and is embedded as a cultural ecosystem services in the ecosystem services provided by flooded rice fields to the society described in the next section. The French law attributes the right to hunt to the owner of the land. However, such rights can then be transferred to someone else, either for free or for a given agreed hunting right lease. A survey conducted by Mathevet (2000) concluded that

the mean income from hunting in the sampled hunting estates was 1,839 French Francs per hectare per year which, including cumulated inflation rates, equates to 358.43 €/ha in 2014. All those three potential benefits from hunting were considered at the scale of the farmer (not society) while computing the benefits-to-costs ratios.

2.4.8. Winter flooding: ecosystem services to the farmer

For the farmer, flooding the fields during winter can bring ecosystem benefits in the form of buffer against floods which amount to 15.16 €/ha after Calvet et al. (2011).

2.4.9. Winter flooding: ecosystem services to society

Besides the potential ecosystem services provided by flooded rice fields in terms of habitat for wildfowling or agronomic+environmental benefits to the farmer, artificial wetlands also provide services to society in terms of 1) support for biodiversity, 2) water quality, and 3) aesthetical landscape value. Through a meta-analysis of Mediterranean wetland data, Calvet et al. (2011; see also Brander et al., 2006) provided estimates which, corrected for inflation until 2014, amount to 5.83 €/ha for support to biodiversity and 17.49 €/ha for water amelioration. Calvet et al. (2011) estimated that the willing to pay by visitors of the Camargue, used as a means to evaluate the aesthetical landscape value, was equivalent to 16.09 € per visit as of year 2014. Considering that 5.3 million individuals visit the Camargue, of which 12% do so during winter (PNRC, 2013c), and that 11,390 ha were cultivated in rice in 2014 (France AgriMer, unpublished data), the total willingness to pay by visitors for such landscapes would be (16.09*5,300,000*0.12)/11,390 = 898.44 €/ha. Combined with the other ecosystem services above the total benefit provided to society by flooded rice fields is 921.76 €/ha.

2.5. Sensitivity analysis

For the sensitivity analysis, the costs and benefits were lumped into higher-order categories, with values varying from -99% (avoiding -100% which would have prevented computation of some ratios) to +200% before re-computing the benefits-to-costs ratios of each of the 6 agricultural scenarios. These higher-order categories were: 1) “Farming costs”, comprising salary, fuel and fixed costs, 2) Irrigation+drainage costs, 3) GHG costs, 4) Agri-environmental incentives, 5) “Hunting income” (comprising food provisioning from hunted game, cultural benefits from hunting enjoyment, and hunting leases), and 6) Ecosystem services (all those listed in the section above, except those from recreational hunting, which were considered above only at the farmer level). In all cases the simulations were calculated separately for the individual farmer and for society (including the farmer). The ranking of the scenarios according to their benefits-to-costs ratio was then evaluated.

3. Results

The total costs, total benefits and benefits-to-costs ratio of each scenario are presented separately for the individual farmer and the whole society, including the farmer (Table 5).

For the farmer, all possible scenarios were economically profitable given that the benefits outweighed the costs (B/C ratios > 1) in all cases. The current burning-ploughing scenario had the lowest benefits-to-costs ratio, while the most beneficial scenario was when the rice was harvested in flooded fields and the chopped straw was later incorporated with a rototiller. The

benefits-to-costs ratio was consistently lower for the scenarios where straw was burnt instead of chopped.

The results were somewhat different when the situation was considered from the society's point of view. First, the burning-ploughing scenario was unsustainable given that costs outweighed benefits (B/C ratio = 0.78). All other scenarios were strongly beneficial, with benefits more than twice to almost seven times greater than costs. Scenarios with flooding yielded the greatest benefits-to-costs ratios and the most beneficial scenario was harvesting in flooded fields. Scenarios with burning instead of chopping of straw were generally less beneficial. It should be noted that the ratios were generally greater for society than for the farmer, which was mostly due to the ecosystem services provide to society by the flooding of fields.

Table 5 Total benefits, total costs and benefits-to-costs ratios (B/C) of each agricultural scenario, when considering the individual farmer or society as a whole (including the farmer).

Scenarios	Total benefits to farmer (€/ha)	Total costs to farmer (€/ha)	B/C ratio to farmer	Total benefits to society (€/ha)	Total costs to society (€/ha)	B/C ratio to society
Burning–ploughing (1)	238.87	234.54	1.02	238.86	304.54	0.78
Chopping–incorporation (2)	351.67	148.76	2.36	351.67	150.93	2.33
Burning–flooding–incorporation–drainage (3)	689.12	417.10	1.65	1610.88	550.80	2.92
Chopping–flooding–drainage–ploughing (4)	801.93	391.41	2.05	1723.69	457.56	3.77
Chopping–flooding–incorporation–drainage (5)	801.93	367.33	2.18	1723.69	433.22	3.98
Harvest in water–chopping–incorporation – drainage (6)	801.93	193.06	4.15	1723.69	258.30	6.67

Changing the value of the costs or the benefits in the sensitivity analysis confirmed the robustness of the above results. Although the benefits-to-costs ratios of the various scenarios were sometimes very different from the initial situation, the ranking of the agricultural options, evaluated from such ratios, was generally conserved except for extreme simulations (virtual disappearance or close to 200% increase of some parameters). Globally speaking harvests in flooded fields were consistently the most profitable option, for both individual farmers and the society (Fig. 1, Fig. 2).

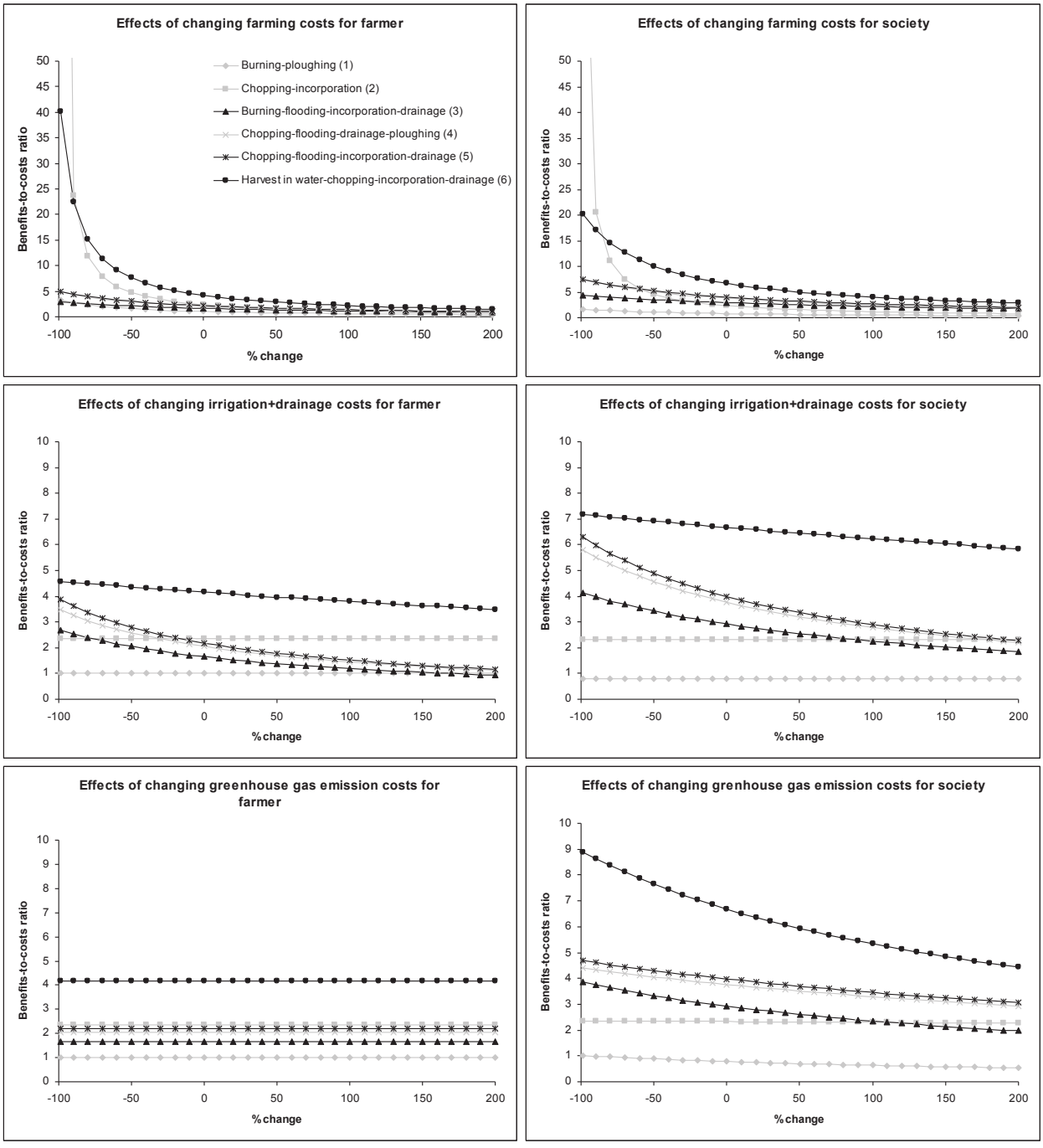

Fig. 1. Effects of changing the value of costs to the individual farmer or society on the benefits-to-costs ratios of the six agricultural scenarios during the intercropping period in Camargue rice fields.

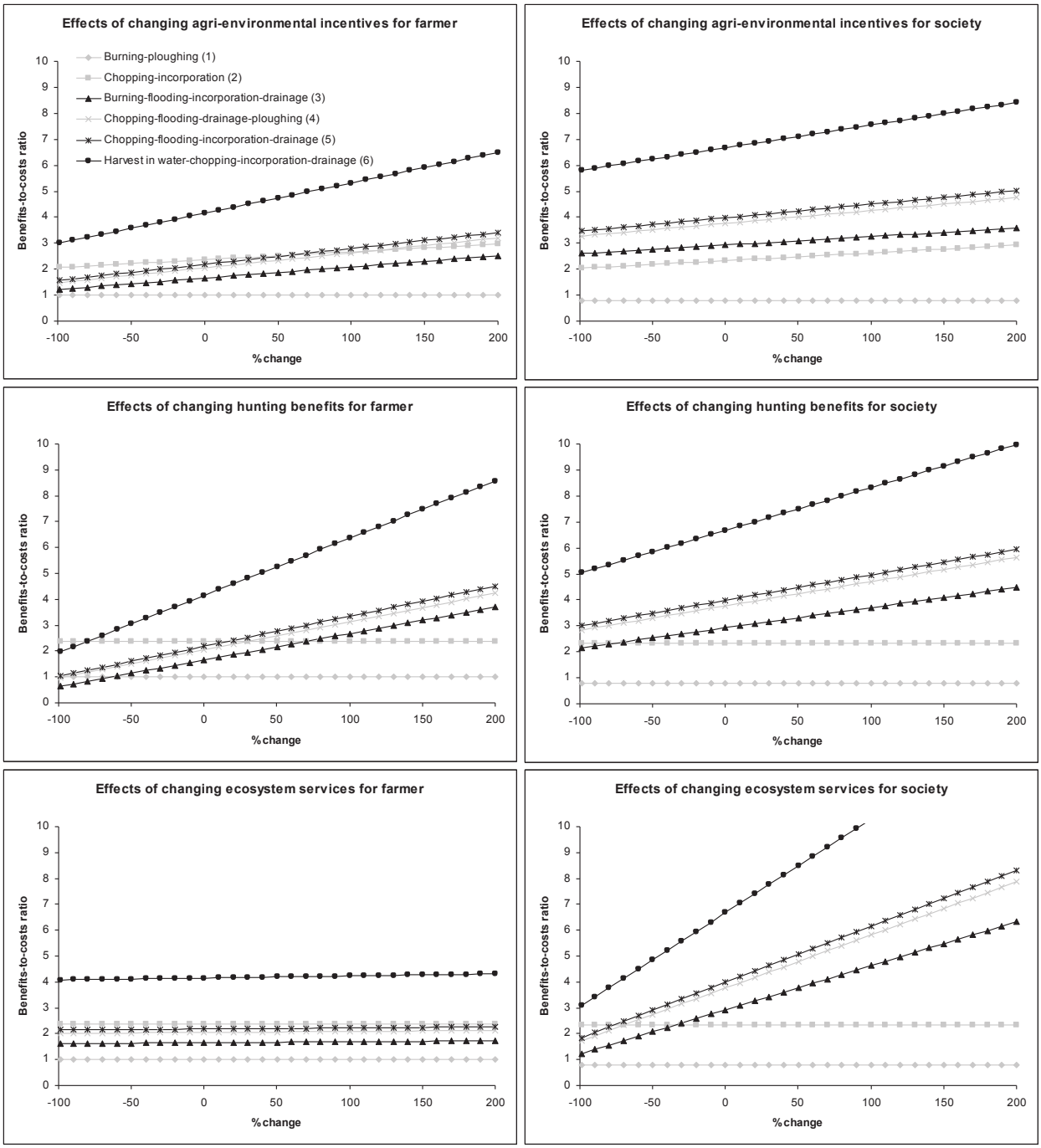

Fig. 2. Effects of changing the value of the benefits to the individual farmer or to society on the benefits-to-costs ratios of the six agricultural scenarios during the intercropping period in Camargue rice fields.

Chopping-incorporation (scenario 2), for which farmers pay little costs apart from salaries, fuel and fixed costs, became the most profitable option when such farming costs were reduced, reaching benefits-to-costs ratios as high as 236 when farming costs were reduced by 99%. However, farming costs had to be reduced by close to 90% before this scenario became more profitable than harvesting in flooded fields. The ranking of the various options otherwise remained globally similar across the sensitivity analysis (Fig. 1).

Increasing the irrigation+drainage costs did not change the ranking of the scenarios for the individual farmer. Yet reducing costs by as little as 20% made most scenarios with flooding more profitable than any dry scenarios. For society, conversely, reducing the costs of irrigation and drainage did not lead to a changes in the ranking of the scenarios, because flooding scenarios were already more profitable in the initial situation. Conversely, increasing the cost of water more than ca. 100% lead to some flooded scenarios becoming less beneficial than dry ones, albeit harvest in flooded fields (when there were no irrigation costs) always remained the best option (Fig. 1).

The cost of greenhouse gas emissions was not considered for individual farmers, thus they were not affected by changes in this parameter. For society, the initial ranking of the scenarios was maintained if the costs of greenhouse gas emissions were reduced. The three best scenarios (those with flooding and chopping instead of burning of the straw) remained the same with up to a 200% increase in such costs (Fig. 1).

Reducing the current agri-environmental incentives did not change the order of the scenarios for farmers. Increasing incentives by ca. 50% lead to scenarios 4 and 5 (chopping-flooding) to become more beneficial than chopping-dry incorporation. For society, changing the value of the agri-environmental incentives changed the magnitude of the difference between the ratios of some scenarios, but the ranking of these remained the same (Fig. 2).

The benefits from hunting are linked with the flooding of fields in our analysis. Reducing the potential income from hunting favoured dry scenarios, while increasing such income promoted the flooded scenarios. With an increase in hunting income greater than 70% all flooded scenarios became more profitable than dry ones for the individual farmer. The income from hunting had to be reduced to almost zero for chopping-dry incorporation (scenario 2) to become the best option for the individual farmer. For society, the flooded scenarios remained the best option even with no income from hunting, with the exception of scenario 3 (burning-flooding-incorporation) when hunting income was reduced by more than 70% (Fig. 2).

The pattern for changes in ecosystem services for society was similar as for hunting: all flooded scenarios greatly benefited from increases in non-market income, but this did not change the ranking of the scenarios compared to the initial situation where they were already more profitable than dry scenarios. Individual farmers were affected only marginally by changes in the ecosystem services, since this only relied to the agronomic+ecosystem services of flooding (i.e. 15.16 €/ha in the initial situation; Fig. 2).

4. Discussion

Worldwide research has repeatedly highlighted the ecological and agronomical benefits that can be expected from flooding rice fields during the intercrop season (reviews in Manley, 2008 for the U.S., in Elphick et al., 2010a or Pernollet et al., 2015a for a worldwide

perspective). However, all of these studies recommend that a precise economic evaluation of such waterfowl-friendly management should be compared to other post-harvest practices in each rice production region. The present study suggests that winter flooding in the Camargue (France) is economically viable for individual farmers as it increases savings on fertilizers and pesticides, and the farmers can benefit from agri-environmental incentives and income from waterfowl hunting. This practice is even more beneficial for the macro society as a wide array of ecosystems services is associated with winter flooding. The sensitivity analysis suggested such results were robust against wide variations in the value of costs and benefits considered here.

4.1. The farmer's point of view

The results of the benefits-to-costs ratio analyses were straightforward when considering the individual farmer's point of view: all scenarios were profitable (benefits-to-costs ratios > 1), but the traditional burning-ploughing had the lowest ratio, while harvesting rice in flooded fields had the best ratio by saving pumping costs. Apart from fees to be paid to ASAs for pumping water in and out of the fields and the cost of pumping water with a tractor-held pump for high lands, the other costs to the farmer were similar among all scenarios considered (Appendix 1). Conversely, the benefits were massively increased with flooded scenarios, owing especially to current agri-environmental incentives and the income from waterfowl hunting that farmer could receive.

The costs of flooding and the use of agricultural machinery are well studied by agronomists and clearly perceived by farmers as well as probably the possible benefits from hunting lease. Conversely, the possible benefits from savings on tillage requirements or fertilizers and pesticides in some post-harvest practices are poorly evaluated, and hence not really considered by farmers worldwide in their economic balance (see however Manley et al., 2005). This could explain why the most common practice in Camargue (burning-ploughing) is actually the least beneficial of the scenarios we tested.

The costs of flooding are known to vary greatly between rice production regions depending on flooding systems: either by pumping such as in California, Texas or Camargue, by gravity such as in the Mississippi Valley, the Delta del Ebro, the Albulfera de Valencia or the Pô Valley, or by winter rain concentration such as in some parts of Portugal or Japan (Shimada et al., 2000; Anders et al. 2008; Lourenço and Piersma, 2009; Pernollet et al., 2015b). In the Camargue, we chose to evaluate such flooding costs as the mean exploitation fee of irrigation and the mean ordinary fee for drainage over all ASAs. We assumed that the fields would be flooded directly after harvest, in October and hence maintain summer electricity prices. This water input, when combined with winter rains, should be enough to maintain the fields flooded until the beginning of February (corresponding to the end of hunting season and before the initiation of the new cultivation cycle). The situation may be different if farmers had to regularly re-flood their fields throughout the winter, which would be associated with greater electricity costs. Finally, it should be kept in mind that we considered an average situation, while owing to specific ASA decisions, the cost of flooding actually varies greatly between sub-regions of the Camargue (min=16.68€/ha, max=180.66€/ha for exploitation irrigation fees and min=0.09€/ha and max=88.57€/ha for ordinary drainage fees, ASAs, unpublished data). Relying on winter flooding would hence be much cheaper for some Camargue farmers than others; however, the sensitivity analysis showed that even profoundly changing the irrigation+drainage costs had little effect on the ranking of the different agricultural scenarios for the farmer.

Agricultural market costs are well known in the rice production systems, mainly concentrating on the cultivation period (e.g. Technical report of Livezey and Foreman, 2004) but also for the intercrop period (e.g. Brouder and Hill, 1995 and Horwath and van Kessel, 2001 in Anders et al. 2008; Bird et al., 2000; Hill et al., 2006). However, potential savings on fertilizers or pesticides made possible by particular post-harvest practices are less evaluated and, as explained above, probably not considered by farmers. Muzzi (1994) and then Manley (1999) and Manley et al. (2005) made an important step in this direction in the U.S. by estimating the possible savings on direct tillage requirement costs, but very little information is available on herbicide and fertilizer savings linked with improved straw and weed decomposition in flooded and non-burnt fields.

The potential income from waterfowl hunting largely contributed to the high benefits-to-costs ratios of flooded scenarios for farmers, and is also recognised as an important business in Camargue private estates (e.g. Mathevet, 2000). The majority of American and European rice farmers that flood their fields after harvest do so to attract ducks for leisure hunting purposes (Elphick et al., 2010b), generating about 4.4 million euros in lease income annually in Camargue (Mathevet and Mesléard, 2002), and representing an economy of about $86.8 million in the US (equivalent to 76.5 million Euros, Grado et al., 2011). In the case where farmers or landowners do not want to promote wildfowl hunting, this could be replaced by any alternative activity (e.g. ecotourism or birdwatching: Kerlinger, 1993 in Eadie et al., 2008) yielding a minimum income of ca. 85 €/ha in Camargue (20% of estimated income from hunting, under which the sensitivity analysis suggests some dry scenarios become more profitable than the flooded ones). Furthermore, farmers could capitalize on additional income opportunities (not considered in the present CBA) from managing fields in a "waterfowl-friendly way" and advertising this by marketing products with a special mark and at higher prices. Such products already exist in other countries, sometimes focusing on other species: Spanish Ebro Delta organic rice, http://www.rietvell.com/, "CheolwanCrane Rice," in Korea, "Ibis Rice" in Cambodia, http://www.wildlifefriendlyorg/ ibis-rice (in Elphick et al., 2010c).

4.2. The society's point of view

The analysis of the benefits-to-costs ratios for society provided somewhat different results than for the single farmer. Non-market costs and benefits, especially those linked with greenhouse gas emissions or ecosystem services, profoundly changed the ratios and strongly increased the advantages associated with winter flooding. Conversely, the current burning-ploughing no longer appeared as a sustainable option when considered from the society's stand point instead of the individual farmer's point of view.

With climate change, the question of GHG emissions continuously gains in importance in societal and individual decisions. Because rice is cultivated in water, this crop is known as a CH4-emitting culture, which is gaining attention in Europe (http://www.sostrice.eu/en/ and http://www.greenrice.eu/about-us/). Flooding rice fields during winter may be detrimental in terms of greenhouse gas emission, but based on our calculations, burning the straw would produce GHG than chopped scenarios. On the other hand, a recent study suggested that post-harvest agricultural practices aimed at reducing GHG emissions could be detrimental to waterbirds (see Sesser et al., 2014). There is therefore a potential conflict of interest between flooding for waterfowl and keeping the fields dry to avoid GHG emissions. This conflicting point of view should be further studied.

The potential benefits from the various scenarios at the society level, mostly linked with the ecosystem services provided by flooded fields, could be quantified thanks to earlier works by Calvet et al. (2011), who estimated the willingness to pay by visitors for such Camargue landscape. This willingness to pay by tourists was used as a mean to evaluate the aesthetical landscape value of the study area and generated the greatest values in our analysis. Such evaluations, which are mostly based on people interviews, has been highly criticized in the past and should be treated with caution. Despite this criticism, we maintained this data in our analysis given that this was the only data of this type available to us and the sensitivity analysis suggested that best scenario remained the same even without any such ecosystem service benefits.

We did identify some costs and benefits to farmers that we could not quantify, and hence these elements were not included in the analyses. Two potential problems that are frequently put forward by farmers as the reason for not flooding the land are the fear that this could prevent early preparation of the fields for the next crop season and the risk of deadly accidents involving cage-wheels, as the tractors may flip over. The successful implementation of winter flooding in North America and Spain partially eliminates the first hypothesis. The latter appears to be a psychological hurdle rather than a real potential. While this has repeatedly happened in Camargue in the past, the modern tractors are generally heavier and have a cabin and/or roll-cages, so the risk of flipping over is reduced. Furthermore, incorporation of straw in flooded fields can now also be done using a rototiller (a new south-korean machinery recently introduced in Camargue and largely used in Spain) rather than cage-wheels, eliminating such risks.

One major benefit from rice cultivation in Camargue is its desalination effect since fields are continuously flooded during the rice growing season, allowing farmers to grow wheat or other highly profitable crops in future crop rotations (Mañosa i Rifé, 1997). Flooding the fields during winter could further contribute to the desalination of the fields, but we were unable to quantify this potential benefit.

At the level of society, some other costs were identified but could not be estimated. Some of these costs included the risk of fire on natural features when burning the straw, uncontrolled flooding from heavy rains in autumn associated with already flooded rice fields and the risk of overexploitation of the water resource if all of the Camargue rice fields were flooded. As explained in the Methods section, the likelihood of the former two events is very low at the scale of one single intercrop season, as considered here. The risk of overexploiting the water resources is negligible in the current Camargue system where water is pumped from the Rhône, one of the main rivers in France with a high debit, close to the river mouth. The situation may be different in other regions using winter flooding, such as in California or in southern Spain, where water supply is limited and competition for water may arise between natural wetlands and irrigated fields (Pernollet at al., 2015a). Nevertheless, it should be kept in mind that things may change in the future if the river debit decreases in the alpine tributaries due to decreased snow pack and glaciers. In this case, a salt wedge could move upstream from the Rhône mouth, increasing the salt levels in the river and making the water inappropriate for agricultural irrigation (e.g. Chauvelon et al., 2013). Similarly, catastrophic rainfall events linked with climate change may also induce more frequent floods. Assessment studies are currently carried out in the Camargue to improve the drainage systems owing to such potential risks of flood in the future (PNRC, 2013b). Taking into consideration climate change, spatial analyses should be carried out to determine where in the delta it would be both easier and safer to flood and drain the rice fields.

Admittedly, the benefits-to-costs ratio analysis as practiced here may be adequate to analyse current or temporary processes, but it is poorly suited for predicting the outcome of different practices over the long term in a changing environment. To better take into account the future effects of potential climate, agricultural or politic changes, a proper modelling approach such would be more appropriate.

For the time being and for the purpose of the present study, which was limited to assessing the best scenarios for one intercrop period in the short-term, the benefits-to-costs ratios does seem to be a valuable approach. The sensitivity analyses at both the individual farmer and the society scale highlighted the robustness of the results, since the ranking of the scenarios remained consistent across changing values of the costs and benefits.

4.3. Conclusion: implications and prospect

The actual and traditional burning-ploughing practice barely reaches a financial equilibrium for the farmer and was associated with great costs than benefits at the society level (benefits-to-costs ratio < 1). This was linked with the scenario providing none of the ecosystem services that flooded fields can bring, while simultaneously being associated with both high agronomic costs to farmers (in terms of fertilizers to compensate losses to fire) and high non-market costs through greenhouse gas emissions for society. Burning the straw is only tolerated through derogation in Camargue. Once this derogation ends, the farmers will be required to switch to other means of straw disposal (like in California, California Rice Straw Burning Act 1991 in Anders et al., 2008)). The present results suggest that chopping and later incorporating or flooding+incorporating the straw is economically feasible for the individual farmer and preferable from a societal point of view.

The current analysis shows that it would be economically feasible for rice farmers to implement winter flooding in the Camargue, even if farmers have to pump water from the river to flood the fields. Raising awareness and providing information to the agricultural community about the possible benefits brought by flooding may help promote the implementation of this technique, yet there may still be some psychological hurdles to overcome. Among flooded scenarios, keeping water from the rice growing season until post-harvest, with harvest in flooded fields, appears like the most beneficial option, since this relieves farmers from paying additional irrigation costs. According to the information that we were able to obtain, only one rice farmer in the Camargue is currently harvesting in flooded fields, making it difficult to determine exact agronomic outcomes within this specific geographic region. In particular, keeping the fields flooded during summer and early autumn may increase the risk of crop lodging, or may cause the straw to remain greener and hence more difficult to decompose (Thomas C., CFR, com. pers.). We hence recommend introducing the flooding of harvested fields in Camargue rice farms, but also that such fields be simultaneously studied and monitored by agronomists to better assess the later consequences in terms of crop yield and other agricultural issues. One way to do so could be to promote exchanges with Spanish agronomists and farmers that already have more than 15 years of experience in harvesting, rototiller use and weed management in winter flooded conditions. Another low-cost procedure that should be explored is the passive harvest of rain through improving water retention (e.g. in Japan, Shimada et al., 2000; in Portugal, Lourenço and Piersma, 2009). With an average of 58.0 mm rain between October and February and a maximum of 90.6 mm in October (1977-2006, PNRC, 2013b), rainfall could provide the minimum suitable water depth of 5 cm for dabbling ducks during winter in the Camargue (with the exception of particularly windy winters).

Flooded scenarios were economically feasible for farmers and highly beneficial to society. Although these scenarios are already beneficial to farmers, it may be useful to provide financial incentives to farmers in order to promote winter flooding, while still having benefits-to-costs ratios well above 1 for the general public. Diverse ways of payments are already implemented to promote winter flooding of rice fields in the U.S. and in Japan by the federal government (Eadie et al., 2008; Natuhara, 2013) and some NGO funds are also used through reverse auctions (BirdReturns Project, The Nature Conservancy, 2014). In Europe, Spanish rice farmers of the Ebro Delta and Albufera de Valencia can apply for ca. 60 €/ha through agri-environment schemes to flood their fields for a minimum of 3.5 to 4 months during winter, resulting in the creation of an immense artificial wetlands available to waterfowl in these RAMSAR sites (Albufera, Law: RD 4/ 2001 and RD 708/2002, Ebro Delta: Council Regulation (EC) No 1257/1999 in Pernollet et al., 2015b). In both regions, as in the Pô valley in Italy where harvested rice fields are kept dry during winter, flooding costs are lower than in the Camargue since water comes to the fields by simple gravity (Pernollet et al., 2015b).

CBA can be a useful tool for decision-making in a given area and for a given time period, but it does not provide universal results applicable to every situations. The results regarding the potential feasibility of winter flooding in Camargue were clear-cut, and may apply to other similar rice cultivation systems; however, a nuanced approach of the CBA which weighs the site-specific costs and benefits of winter flooding is necessary for further comparisons (Boyer, 2013).

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Appendix 1. Costs associated with the six agricultural scenarios (the numbers in parentheses correspond to the activities in Table 1). Crosses indicate costs known to exist but not quantified in the present analysis.

	Burning - ploughing (1)	**Chopping - cover-crop (2)**	**Burning - flooding - cage-wheels - drainage (3)**	**Chopping - flooding - drainage - ploughing (4)**	**Chopping - flooding - rototiller - drainage (5)**	**Harvest in water - chopping - rototiller - drainage (6)**
Costs to farmer (€/ha)						
Salary costs	30.39	25.18	39.69	34.49	30.98	30.98
Fuel consumption	51.97	39.13	37.63	58.18	43.83	43.83
Fixed costs[1]	82.77	84.45	109.05	137.42	131.20	100.03
Fertilizers to compensate nutrient losses to fire	69.41		69.41			
Irrigation costs[2]			143.10	143.10	143.10	
Drainage costs			18.22	18.22	18.22	18.22
Damage of soil structure*	X			X		
Inability to rotate crops*			X	X	X	X
Crop lodging risk *						X
Late drying of soils*			X	X	X	X
Mortality risk while using cage-wheels*			X			
Costs to society (€/ha)						
Risk of fire*	X		X			
Flooding risk*			X	X	X	X
Overexploitation of water resources*			X	X	X	X
Greenhouse gas emissions	70	2.17	133.70	66.15	65.87	65.24

1 includes insurance, amortization and storage costs
[2] values for high lands, where the pumping costs are greater
* not quantified in the present study

Appendix 2. Benefits associated with the six agricultural scenarios (the numbers in parentheses correspond to the activities in Table 1). Crosses show benefits known to exist but not quantified in the present analysis.

	Burning – ploughing (1)	**Chopping – cover-crop (2)**	**Burning – flooding – cage-wheels – drainage (3)**	**Chopping – flooding – drainage – ploughing (4)**	**Chopping – flooding – rototiller – drainage (5)**	**Harvest in water – chopping – rototiller – drainage (6)**
Benefits to farmer (€/ha)						
Reduced need for fertilizers (stalks and/or straw incorporation)	13.60	81.65	13.60	81.65	81.65	81.65
Reduced need for herbicides (seed degradation and/or crop rotation)	225.26	225.26	52.90	52.90	52.90	52.90
Reduced weeds and rice diseases*	X		X			
Improvement of soil structure*		X			X	X
Rapid implementation of next cultivation phase*	X	X				
Agri-environmental incentives		44.76	180.74	225.50	225.50	225.50
Desalination of fields*			X	X	X	X
Buffer against floods			15.16	15.16	15.16	15.16
Leisure hunting (own hobby)			46.65	46.65	46.65	46.65
Hunting (food source)			21.64	21.64	21.64	21.64
Income from hunting leases			358.43	358.43	358.43	358.43
Benefits to society (€/ha)						
Landscape aesthetic value			898.44	898.44	898.44	898.44
Promotion of biodiversity			5.83	5.83	5.83	5.83
Water quality improvement			17.49	17.49	17.49	17.49

1 includes insurance, amortization and storage costs
* not quantified in the present study

APPENDIX I.2

Disentangling the drivers of change in Common Teal migration phenology over 50 years: land use vs. climate change effects

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ORIGINAL ARTICLE

Disentangling the drivers of change in Common Teal migration phenology over 50 years: land use vs. climate change effects

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Abstract A large body of research has accumulated on the impact of climate change on wildlife movements and distributions, especially for migratory birds. We used large ringing datasets for the Common Teal (*Anas crecca*) from the Camargue, southern France, to compare historic (from 1956–1975) spatiotemporal patterns of teal recovery with those seen in modern (2002–2012) years and assess whether the migration phenology of these ringed birds and their use of the Camargue as winter quarters has changed. Because teal are short-distance migrants (i.e., they breed in northern Europe and winter north of the Sahara), they would be predicted to delay their autumn migration in response to climate change. Conversely, ring recoveries showed that teal are now arriving much earlier: a stable 80 % of the recoveries were made locally in the Camargue each week between mid-November and late January in the modern dataset, whereas this percentage was only 53 % on average in the older data, and the proportion of recoveries made locally in the Camargue gradually increased through the autumn and winter until late January. This suggests that Camargue habitats have changed markedly and become more attractive to teal compared to other potential wintering areas, consistent with known changes in local habitat management practices and improvements in the body condition of the birds. Despite the fact that global climate change will likely be one of the main drivers of wildlife distribution over the long term and at large spatial scales, local habitat management should not be overlooked, as it can increase habitat attractivity to migratory birds.

Keywords *Anas crecca* · Autumn migration phenology · Camargue · Climate change · Land-use change · Ring recoveries

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Zusammenfassung

Entflechtung der Einflussfaktoren auf die Phänologie des Zugverhaltens der Krickente über 50 Jahre: Landnutzung oder Klimawandel?

Es gibt inzwischen eine Vielzahl von Studien zu Einflüssen des Klimawandels auf Bewegungsmuster und Vorkommen von Wildtieren, insbesondere von Zugvögeln. Wir nutzten hier einen großen Datensatz zur Beringung der Krickente *Anas crecca* aus der Camargue in Südfrankreich, um die räumlich-zeitlichen Verteilungsmuster der Wiederfunde zwischen alten (1956–1975) und jungen (2002–2012) Jahren zu vergleichen und zu überprüfen, ob sich die Phänologie des Zuges dieser beringten Vögel und ihre Nutzung der Camargue als Winterquartier zwischenzeitlich geändert hat. Da Krickenten Kurzstreckenzieher sind (sie brüten in Nordeuropa und überwintern nördlich der Sahara), wurde angenommen, dass sich ihr Herbstzug aufgrund des Klimawandels verzögern würde. Gegensätzlich stellte sich

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aber heraus, dass Krickenten heutzutage viel früher ankommen: es wurden stets um die 80 % der Wiederfunde jede Woche zwischen Mitte November und Ende Januar in der Camargue verzeichnet, während im alten Datensatz dieser Prozentsatz bei nur etwa 53 % lag, sich aber über den Herbst bis hin zum Ende des Januars erhöhte. Dies deutet darauf hin, dass die Lebensräume in der Camargue sich stark verändert haben und für Krickenten attraktiver geworden sind im Vergleich zu anderen möglichen Wintergebieten. Dies ist im Einklang mit bekannten Veränderungen in der Landnutzung vor Ort und einer verbesserten Körperkondition der Vögel. Obwohl der globale Klimawandel wahrscheinlich langfristig und über große geographische Flächen einer der Haupt-Einflussfaktoren der Verteilung von Arten sein wird, so ist doch die Nutzung der Flächen vor Ort ein wichtiger Faktor, der die Attraktivität eines Lebensraumes für Zugvögel erhöhen kann.

Introduction

An abundance of literature has been published on the consequences of climate change for wildlife over the last 15 years, which has allowed general patterns to emerge. In migratory birds, the most commonly documented effects are shifts in migration phenology and geographic distribution (e.g., Thomas and Lennon 1999; Hughes 2000; McCarty 2001; Crick 2004; Rainio 2008; Knudsen et al. 2011). It seems to be a general rule that climate warming has resulted in earlier springs, which most migratory birds attempt to track by advancing their prenuptial migration and/or breeding dates (e.g., Rainio et al. 2006; Thorup et al. 2007; Jonzén et al. 2006; Gordo and Sanz 2006; Gordo 2007; Lehikoinen and Sparks 2010; see, however, Gordo et al. 2013 for complex patterns within some populations). The situation is not so clear for autumn migration, where advanced, delayed, or stable departure dates from the breeding grounds have all been documented (e.g., Adamík and Pietruszková 2008; Barshep et al. 2012; Chambers et al. 2014). However, long-distance European migrants wintering south of the Sahara seem to depart as early as possible to benefit from favorable migration conditions en route to their wintering grounds, hence showing advanced autumn migration; conversely, short-distance migrants wintering in Europe or North Africa tend to show delayed autumn migration, apparently trying to benefit from extended favorable conditions at the breeding grounds (Jenni and Kéry 2003; Tøttrup et al. 2006; Gordo 2007; Filippi-Codaccioni et al. 2010). Furthermore, some species now encounter favorable wintering conditions at higher latitudes, hence shortening their migration distances ("short-stopping," e.g., Visser et al. 2009; Gunnarsson et al. 2012; Heath et al. 2012; "partial winter short-stopping" after the definition in Elmberg et al. 2014).

In most cases, climate change will have seemingly slow effects (although very clear and consistent in the long term, and potentially with dramatic consequences), e.g., the boundaries of 99 species of birds, butterflies, and alpine herbs have moved 6.1 km polewards per decade (Parmesan and Yohe 2003), and the spring arrival dates of a variety of birds have advanced by 2.3–3.7 days on average over the same time frame (Chambers et al. 2014). Besides changes in climate, changes in land use and habitat management have the potential to affect the distributions and movement patterns of migratory birds more abruptly (see discussion in Fiedler et al. 2004). Of course, some changes in habitat are linked to changes in climate (e.g., through altered rainfall patterns or freezing conditions, leading to changes in plant communities). However, many habitat changes are also linked with human activities (e.g., through habitat transformation for agriculture, eutrophication, etc.). In some situations, the predicted consequences of land-use and climatic changes for wildlife are different, allowing us to test the influences of these two factors on wildlife abundances and distributions in the short term, keeping in mind that, in many cases, the effects of climate change will also manifest themselves and often dominate over the longer term.

Waterfowl (*Anatidae*) are among those species likely affected by the consequences of both climate change (e.g., Lehikoinen and Jaatinen 2012; Guillemain et al. 2013; Lehikoinen et al. 2013) and changes in land use (e.g., Duncan et al. 1999). Indeed, these birds have advanced their spring migration dates and have reached their breeding grounds increasingly early over the last few decades, likely in response to climate change (e.g., Nilsson 2006; Pistorius et al. 2006; reviews in Dalby 2013, Guillemain et al. 2013). Gradual shifts in winter distribution have also been documented (e.g., Švažas et al. 2001; Nilsson 2008; Sauter et al. 2010; Gunnarsson et al. 2012; Lehikoinen et al. 2013). Waterfowl are also known to quickly respond to habitat deterioration (e.g., Duncan et al. 1999; Long et al. 2007). Conversely, adequate habitat management and reserve creation have translated into dramatic shifts in waterfowl distribution and increased numbers at the local, regional, or flyway scales (e.g., Owen et al. 1986; Madsen 1998; Mathevet and Tamisier 2002; Guillemain et al. 2002; Fleskes et al. 2005; Toral and Figuerola 2010).

Because they are the smallest of all waterfowl species, Common Teal (*Anas crecca*, hereafter "teal") should have the largest relative energy needs, and should thus be especially choosy in their habitat selection processes (Miller and Eadie 2006). They are therefore very suitable candidates for studying the effects of both climate and

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habitat changes. Existing studies have documented earlier breeding of teal after milder springs (Arzel et al. 2014) and a long-term shift towards earlier spring migration dates, as observed in Finland at Hanko Bird Observatory (A. Lehikoinen, pers. comm.; see also Green-winged Teal *Anas carolinensis* in Murphy-Klassen et al. 2005). Colonization of new wintering areas at the northern end of the species range has also occurred, both in Europe and in North America (Nilsson 2008; La Sorte and Thompson 2007, respectively).

In a previous paper, the large (ca. 60,000 individuals) ringing dataset accumulated between the 1950s and the 1970s by the Tour du Valat, Camargue, southern France, was used to describe teal migration phenology (Guillemain et al. 2006). This analysis showed that Camargue-ringed teal migration was slow and extended across autumn and winter, and was immediately followed by the departure of the earliest birds for spring migration as early as early February. Teal captures in Camargue were interrupted after the mid-1970s and were not reinitiated until the early 2000s. A comparison of these two datasets suggested that major changes in the wintering conditions of teal have occurred over the decades, which have translated into a body mass increase of up to 11.7 % between the old and the modern periods (Guillemain et al. 2010). Increased food availability and climate change were proposed as two possible explanations for this massive change in body condition. In the work reported in the present paper, we compared the migration pattern of the teal ringed recently in Camargue to the results in Guillemain et al. (2006) to assess the relative roles of habitat and climate change in shaping the migration pattern of these birds. In particular, we aimed to determine if these birds have changed their autumn migration phenology. If any change had occurred and was related to climate change, a delay in autumn migration was expected, given that teal are short-distance migrants. We also checked for increased use by teal of the Camargue as a wintering site by analyzing the proportion of birds that returned to this area in successive winters, which would be expected if the changes in body condition noted in Guillemain et al. (2006) are mostly due to a general improvement in the Camargue habitats.

Methods

The old Tour du Valat Teal dataset comprises 59,187 individuals that were ringed in the Camargue (43°30′28″N, 04°40′07″E) with baited funnel traps (Bub 1991). 9,279 of these birds were later recovered (mostly by hunting) throughout Europe. Here, we focused on the 5,555 birds that were recovered after the following breeding season, i.e., inter-annual recoveries (see Guillemain et al. 2006 for details of the old dataset). Recoveries made within the same winter as the ringing event (i.e., intra-annual recoveries) were not considered here since we were interested in events that occurred throughout the year, including the autumn migration, while ringing mostly occurred during winter. The Camargue wintering grounds are towards the southwestern end of this population's annual geographic range, so, in both the old and the modern datasets, we considered that birds recovered in areas lying northeast of the Camargue were on their breeding grounds or were migrating from/towards them (Fig. 1). Recoveries that occurred within a 200-km square centered on Tour du Valat were considered to have been made at "local" wintering grounds (see also Guillemain et al. 2006). The old dataset comprises ring recoveries made between August 1956 and April 1975. Within each year, ring recovery data were pooled per week starting on 1st August (i.e., pooled for each of 52 possible weeks per year). The year or season afterwards refers to the period between August of year n and July of year $n + 1$ (e.g., the 1960 season corresponds to the period between 1st August 1960 and 31st July 1961).

The modern dataset also consists of information derived from teal ringed in the Camargue: partly (19 %) in Tour du Valat, but mostly (76 %) in the Réserve Naturelle des Marais du Vigueirat (9 km to the west), and to a lesser extent (5 %) in the Domaine des Montilles de Capette (24 km east of Tour du Valat). The exact locations of teal roosts within winter quarters fluctuate over time following changes in local habitat management procedures or land

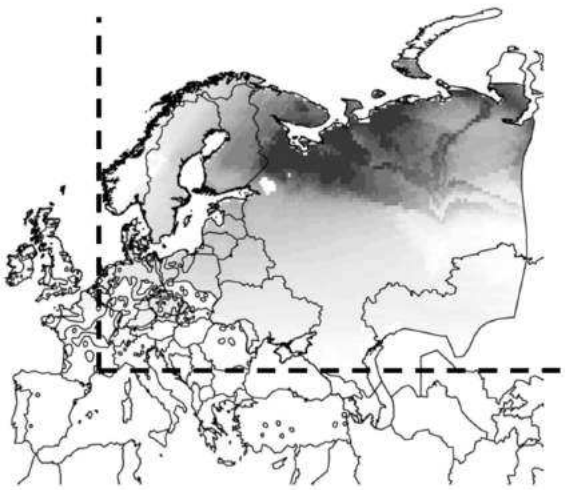

Fig. 1 Teal wintering in France mostly breed in areas to the northeast of the Camargue (*darker zones* indicate a greater probability of origin after stable isotope analyses, modified from Guillemain et al. 2014). Thus, in all analyses we considered that ring recoveries made in areas lying northeast of the Camargue corresponded to birds at their breeding grounds or migrating to/from them

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protection measures (a process described in Guillemain and Elmberg 2014), so capture sites were moved within the Camargue to where teal were most abundant. Because the analyses consider ring recoveries at the flyway scale, and the "local" area was a 200-km square, such local changes in ringing sites should have had no significant effect on the results. A total of 136 inter-annual dead recoveries made throughout Europe between August 2003 and November 2013 were available for analyses from among the 2,324 teal initially ringed in the Camargue over the modern 2002–2012 period. Because no sex or age effects were detected in Guillemain et al. (2006), these factors were not considered in the present analyses, and all individuals in the dataset were taken into account—even those that were not sexed or aged at ringing, so there was a slightly different total number of data in the old dataset used in the present work than in the dataset provided in the earlier reference.

We created a binary variable stating whether recoveries were local to the Camargue (i.e., within a square 200 km on a side) or were made in areas lying northeast of the Camargue. Postnuptial migration phenology was thus assessed from changes in the weekly probability of recovery to the northeast, which decreased as the birds gradually moved—and were recovered—within the local area instead (see also "Methods" in Guillemain et al. 2006). The slope in the gradual change in the probability of recovery in areas lying northeast of the Camargue over the course of weeks was hence indicative of migration speed, with a greater migration speed corresponding to a steeper rate of decrease. We used logistic regressions to determine how this probability was affected by period (old dataset vs. modern dataset, i.e., 1956–1975 vs. 2003–2013), week, and period × week. Such analyses were conducted separately for the autumn (weeks 1–14, i.e., early August to mid-November) and for the core of the wintering season (weeks 15–27, i.e., mid-November to late January). It is important to note that, since all birds in the dataset were initially ringed in the Camargue, the proportion of ring recoveries in the "local" area indicates the likelihood that birds ringed in the Camargue will come back to winter again in the same area over successive years. Because the hunting season now closes at the onset of spring migration (i.e., 31st January, end of week 27) in France, as it does in several other European countries, and most teal recoveries (i.e., 96 % in the modern dataset) are performed by hunters, it was impossible to study the spring migration process with this method. This problem did not arise in Guillemain et al. (2006) because the French hunting season lasted until the end of March in the Camargue until the mid-1970s (Mondain-Monval et al. 2009). Thus, no attempt was made to compare the spring migration phenologies between the two datasets.

The logistic regressions were restricted to ring recoveries made in the local area or in areas lying northeast of the Camargue; recoveries made in other areas/azimuths were discarded (see the above description of the created binary variable). However, very few recoveries were made outside of this presumed migration corridor, since the local plus northeastern recoveries represented 82.45 and 86.77 % of the total dataset in the old and modern samples, respectively. The final dataset used in the analyses was therefore composed of 3,543 recoveries made during weeks 1–27 in the old dataset (782 local and 2,761 in areas lying northeast of the Camargue) and 116 recoveries recorded for the modern dataset (77 local and 39 in areas lying northeast of the Camargue). All statistical analyses were performed with Statistica 10.0 (Statsoft 2011).

Results

The mean weekly proportions of the recoveries that were made in areas lying northeast of the Camargue in the old and the modern datasets are shown in Fig. 2a. The logistic regression testing for a week effect while considering potential differences between periods (old versus modern years) and the period × week interaction highlighted very different patterns of autumn migration (weeks 1–14): in addition to the week effect, which led to a decreasing probability of recovery in areas lying northeast of the Camargue over time during the autumn, this probability differed significantly between old and modern years, although the period × week interaction did not have a significant effect (Table 1). Thus, the speed of migration did not seem to differ between the two periods, as judged by the lack of a period × week effect, but modern birds reached the Camargue much earlier, leading to a lower probability of recovery in areas lying northeast of the Camargue (Fig. 2b).

The mean weekly proportion of recoveries in the local Camargue area during winter (weeks 15–27, i.e., mid-November to late January) was much greater during the modern years than during the old years (0.80 ± 0.06 SE, $n = 10$ mean annual values and 0.53 ± 0.03 SE, $n = 19$, respectively). The probability of teal recovery in areas lying northeast of the Camargue during winter (i.e., still migrating) did indeed differ markedly between the two periods (Table 1). While the week effect was globally nonsignificant, the period × week interaction was significant, indicating differences in slopes. During the modern years, the mean weekly probability of recovery in areas lying northeast of the Camargue did not change significantly over the weeks (estimate of the week effect: 0.08 ± 0.09 SE, 95 % CI: −0.10–0.26), while it decreased over the weeks during the old years (estimate:

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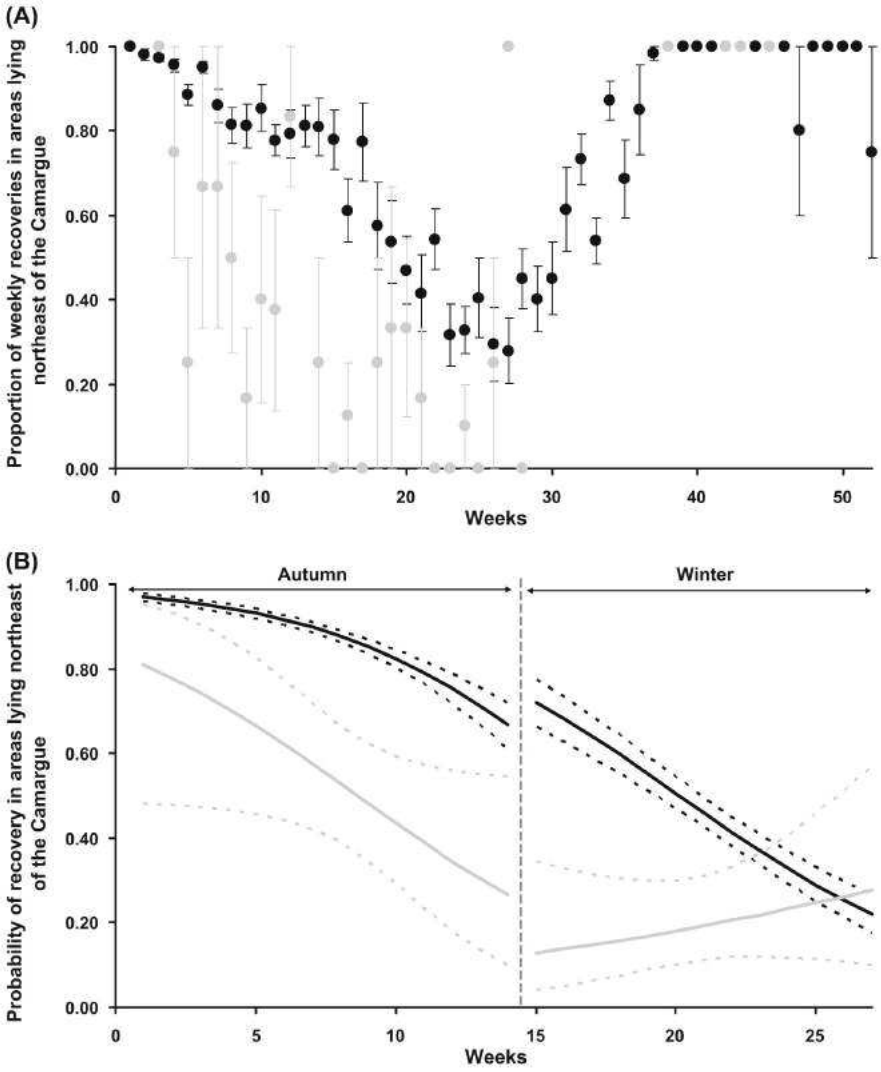

Fig. 2 **a** Mean proportions (±SE) of inter-annual teal ring recoveries made in areas lying northeast of the Camargue over weeks during the old (1956–1974, *black dots*) and modern (2003–2013, *gray dots*) periods, from 1st August to 31st July (i.e., weeks 1–52). Averages were computed from annual weekly data into which individuals of both sexes and age classes were pooled. **b** Modeled probabilities that inter-annual teal ring recoveries were made in areas lying northeast of the Camargue over the weeks during the autumn (weeks 1–14, August to mid-November) and the winter (weeks 15–27, mid-November to late January) during the old (*black*) and modern (*gray*) years. *Dotted curves* show 95 % confidence intervals. See Table 1 for model estimates. Note that the scale on the *x*-axis differs from that used in **a**

−0.19 ± 0.02 SE, 95 % CI: −0.22 to −0.15), reflecting the extended postnuptial migration lasting most of the winter during the 1956–1975 years.

Discussion

Land-use and climate changes in Europe have profoundly transformed the wetlands used by waterfowl over the last decades. The consequences of these changes for the population sizes, distribution, and spring phenology of these birds are already readily apparent (e.g., Owen et al. 1986; Rüger et al. 1986; Toral and Figuerola 2010; Dalby 2013; Guillemain et al. 2013; Lehikoinen et al. 2013). The results of the present study show clear changes in teal phenology at the southern end of their wintering range. The Camargue, which has been known as one of the main winter quarters for these birds in western Europe for decades (e.g., Scott and Rose 1996), is now reached by ringed birds earlier in autumn than it was in the past, and the fidelity of the ringed birds to this area over successive years has greatly increased compared to 50 years ago.

Teal are short-distance migrants that winter north from the Sahara (Scott and Rose 1996). It was therefore expected that these birds would increasingly delay their autumn migration if such movements were primarily driven by climate change, so as to gain the maximum benefit from remaining in their northern breeding areas for extended periods (Jenni and Kéry 2003; Tøttrup et al. 2006). We actually observed the opposite, since a greater part of the

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Table 1 Results of logistic regressions testing for the effects of period (old years 1956–1974 versus modern years 2003–2013), week, and period × week as possible explanations for variations in the weekly probability of ring recovery in areas lying northeast of the Camargue (as opposed to locally in the Camargue)

Effect	Estimate (SE)	Wald stat	*P* value
Autumn migration (early August to mid-November)			
Model fit: Hosmer–Lemeshow test = 45.737, $p = 2.6669$			
Period (old)	1.02 (0.44)	5.32	0.0211
Week	−0.20 (0.05)	16.57	<0.0001
Period × week	−0.01 (0.05)	0.05	0.8166
Wintering (mid-November to late January)			
Model fit: Hosmer–Lemeshow test = 11.046, $p = 0.1990$			
Period	3.42 (1.00)	11.68	0.0006
Week	−0.05 (0.05)	1.28	0.2571
Period × week	−0.13 (0.05)	8.06	0.0045

ringed population reached the Camargue by mid-November in modern years, whereas these birds were still largely engaged in postnuptial migration until as late as mid-January in the old Tour du Valat database. The present analysis did not detect any significant effect of the period × week interaction during the autumn, so it could not demonstrate any significant difference in migration speed. However, there were few ring recoveries during the first few weeks (i.e., August), so it is possible that any difference in slope between the old and modern years remained undetected. More work on the nesting grounds is needed to properly assess exactly when these birds leave the breeding zone, and hence to be more definitive about their autumn migration speed.

In any case, it seems that ringed teal now reach the Camargue wintering grounds much earlier than they did 50 years ago. Besides a general increase in the mean annual temperature, climate change can also manifest itself in changes in the intensity of extreme events (including cold spells) or changes in precipitation regimes (e.g., IPCC 2012). This could theoretically affect teal migration phenology: if cold spells tend to occur increasingly early in the season, or greater autumn precipitations lead to earlier flooding of temporary marshes, then these ducks could tend to arrive increasingly early in the Camargue during the autumn. However, cold spells significant enough to cause massive movements of dabbling ducks in Europe tend to occur much later during the year, mostly in January or February (e.g., Sauter et al. 2010). There is no sign of an increase in annual rainfall in the Camargue since the 1940s either: while some years have been very wet recently, this was mostly because of heavy rains in spring rather than in autumn (Kayser et al. 2014).

Instead of climate change being the main driver of autumn migration phenology, the results thus suggest that the Camargue is now more attractive to ringed teal than it was in the past. Beyond autumn migration phenology, the second set of results also supports the hypothesis of increased attractiveness of the Camargue: while the percentage of local recoveries was only 53 % between mid-November and late January (weeks 15–27) in the old dataset, this percentage is now 80 % on average, with no trend observed over the season.

One possible bias in the present analysis relates to changes in the probability of ring recovery over the years. It is clear that this has declined over time, since the number of inter-annual recoveries represented as much as 9.4 % of the total number of ringed individuals in the old dataset, while this proportion fell to only 5.9 % over the last decade. However, this should not be an issue here, as we have only compared the relative proportions of recoveries in different areas, not absolute ring recovery rates.

What could be a problem with the present study would be a differential rate of change in ring-recovery probability among geographic regions (see Korner-Nievergelt et al. 2010 for the consequences of unequal observer distribution on the results of analyses based on ring re-encounter data). A larger increase in harvest rate or ring return probability in the Camargue than in other geographic areas would produce a pattern similar to our results even without changes in bird migration and distribution over the two periods. This is inherent to most bird-ringing schemes (review in Thorup et al. 2014). However, the main change in hunting policy in Europe has been a general shortening of the hunting season, mostly because the hunting season has closed earlier (e.g., Guillemain and Elmberg 2014 for France). This should not bias the present analysis, as it is limited to the end of January, which is when the hunting season ends in many countries. Another major change is the ban on teal hunting in the Netherlands, which was enacted in 2002. However, the Dutch recoveries during autumn and winter represented only 4.5 % of the total number of recoveries, and a comparison of the old and the modern datasets without the Dutch recoveries in the former period during preliminary analyses yielded the same results (not shown). Finally, a published comparison of the Camargue and British teal ringing databases (the only published comparison of this type) indicated that the proportion of recovered rings changed at a similar rate over the years in the two geographic areas (Guillemain et al. 2011). It is thus most likely that the present results indicate genuine changes in autumn migration phenology and the use of the Camargue by ringed teal rather than a methodological artefact.

It should be kept in mind that all of the data were recoveries of birds captured and ringed in the Camargue during earlier years, so the proportion of local data is indicative of repeated fidelity to the Camargue winter

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quarters rather than greater site use. In fact, Tamisier (2004) considered that teal numbers in the Camargue actually decreased from 1964 to 2000, so what we have observed is a change in site faithfulness rather than an increase in teal numbers (see also Guillemain et al. 2009).

There were more cold spells during the old than the modern years, with particularly severe episodes occurring in the 1955, 1961, and 1963 seasons (e.g., Guillemain et al. 2005). Teal captures were particularly numerous at Tour du Valat during these seasons due to massive affluxes of birds seeking refuge from the cold in these southern winter quarters (see Ridgill and Fox 1990). If the birds returned to their usual wintering sites at higher latitudes the following year, this could have artificially lowered the apparent use of the Camargue inferred from inter-annual ring recoveries in the old dataset. However, the mean percentage of local Camargue recoveries in years following cold winters (i.e., the 1956, 1962, and 1964 seasons) was 26.16 (±3.91 % SE, $n = 3$ annual means), while it was 27.77 % (±1.58 % SE, $n = 16$ annual means) after mild years in the old data, which was not significantly different (t test on arcsine-transformed proportions: $t_{17} = 0.41$, $P = 0.61$). The observed low fidelity to the Camargue in the old dataset was therefore unlikely to simply result from a meteorological artefact in the field.

All results therefore suggest that the Camargue is now more attractive to wintering teal than it was 50 years ago, at least for birds which used the area in earlier years (i.e., recovered ringed birds). Some known changes in Camargue habitats may explain this pattern. First, the area under official protection status has increased ca. threefold; it currently comprises approximately 40,000 ha or 20 % of the delta area (Blondel and Picon 2013). The creation of such reserves has proven to be particularly effective in attracting teal (Mathevet and Tamisier 2002). Hunting pressure on ducks has likely decreased in the Camargue over the last few decades (Mondain-Monval et al. 2009), and the hunting estates (i.e., private properties where hunting is practiced) have also been greatly modified, with more active management of habitats and especially water in recent years: hunting marshes are now flooded with freshwater for longer periods of time in order to provide wetlands for migratory birds at the onset of the hunting season in August and to promote the growth of hydrophyte beds on which ducks can forage (Tamisier and Grillas 1994). Baiting is also increasingly practiced using rice seeds or other crops which are consumed by ducks, including teal (Brochet et al. 2012). Similar baiting practices have been demonstrated to be particularly attractive to wintering waterfowl and to potentially affect their regional distributions (Martínez-Abraín et al. 2007). The provision of safe protected areas plus abundant food in hunted zones likely benefits the teal (in terms of energy balance), and we actually observed a massive 12 % increase in the body condition of these birds when comparing the old to the modern years (Guillemain et al. 2010). These birds likely belong to the same population and have a similar geographic origin in both the old and modern samples (Guillemain et al. 2014). This situation is similar to the one described in Berthold and Terrill (1988), where the migratory behavior and distribution of Blackcaps (*Sylvia atricapilla*) were modified by supplementary feeding by humans. It should, however, be noted that the seeming improvement of the Camargue wintering habitat for teal raises conservation concerns. In particular, changes in the flooding regime of otherwise temporary wetlands are considered detrimental to biodiversity, as they lead to the loss of typical Mediterranean plants and the promotion of more common species (Tamisier and Grillas 1994). It should also be realized that while the present results suggest a greater relative attractiveness of the Camargue to ringed teal, they do not provide any information regarding the actual number of individuals using the area: rather than the Camargue habitats becoming more attractive to teal, it is equally possible that habitats in other areas have deteriorated, so the Camargue habitat has only improved relatively speaking.

It is clear that climate change will have overriding effects on waterfowl and other birds over the coming decades, with further expected consequences for their migration phenology and distribution (e.g., Huntley et al. 2007). However, cases such as the teal situation in the Camargue suggest that human-induced habitat changes may also affect the distribution and phenology of migratory waterfowl in the shorter term and should not be overlooked (see also Anthes 2004; Barshep et al. 2012). Similar situations are observed for other waterbirds; for instance, Black-tailed Godwit (*Limosa limosa*) have benefited from man-made artificial wetlands in Spain (Márquez-Ferrando et al. 2014). Actually, this suggests that the roles of land managers and policy makers are even more important in the context of habitat transformation due to global climate change. The great mobility of teal during winter—leading to a high turnover rate of individuals at any winter quarters—was considered to partly explain the ability of such populations to sustain hunting harvests (Caizergues et al. 2011). Whether the observed changes in teal migration patterns have translated into changes in teal survival rates and hence possible population dynamics is currently the focus of study via a capture–mark–recapture analysis (Champagnon et al., in prep.).

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APPENDIX I.3

Becoming sedentary? Changes in Mallard Anas platyrhynchos ring recovery locations over the last 50 years.

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Becoming more sedentary? Changes in recovery positions of Mallard *Anas platyrhynchos* ringed in the Camargue, France, over the last 50 years

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Abstract

Earlier studies from central and northern Europe have found a shortening of the ring recovery distance in Mallard *Anas platyrhynchos*, which was generally attributed to climate change leading to a northwards shift of the wintering range. Here we show that recovery distances for Mallard ringed during winter in the Camargue (southern France), at the southern end of their range, have also shortened over the last 50 years, from a mean of 417 km (s.e. ± 17.4) for birds ringed between 1950–1978 to 74 km (± 28.9) for birds ringed between 2002–2013. In contrast to the studies in other areas, however, the more recent recoveries of Mallard ringed in the Camargue were made to the south and west of where they were previously, and changes in ring recoveries were likely caused by a greater proportion of sedentary birds among the Camargue wintering population. Discarding unlikely methodological biases that may explain the pattern observed, we suggest three non-mutually exclusive hypotheses to explain such a change: a) increased attractiveness of Camargue habitats as a winter quarter, with migrant birds now staying for longer periods and allowing more local recoveries, b) hybridization between resident captive-bred and wild Mallards, and c) former migrants from northern Europe now foregoing long migration to this distant winter quarter due to climate change. Future studies combining genetic and isotope analyses may help in teasing these hypotheses apart, to provide a better understanding of the factors leading to such increased sedentarity.

Key words: *Anas platyrhynchos*, climate change, habitat quality, hybridization, restocking, ring recoveries, sedentarity.

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Studies over the last couple of decades have repeatedly documented shifts in waterfowl geographic ranges and site occupancy, in response to fluctuations in local habitat quality and general climate change (Duncan *et al.* 1999; Švažas *et al.* 2001; Gunnarsson *et al.* 2012; Lehikoinen *et al.* 2013; Jónsson & Afton 2015; Guillemain *et al.* 2015). Climate change is expected to result in increasingly mild winter conditions and hot summers, gradually leading to migratory bird population ranges shifting north-eastwards in western Europe. Huntley *et al.* (2007) provided maps illustrating expected shifts of breeding ranges, based on the environmental needs for a range of bird species. Gunnarsson *et al.* (2012) showed that the mean recovery location during winter of Mallard *Anas platyrhynchos* ringed in southern Sweden shifted *c.* 300 km northeast between the 1960–1970s and the early 21st century (*i.e.* over the last 15 years). Similarly, by analysing ring recoveries from many European countries, Sauter *et al.* (2010) found that Mallard continued to move to the southwest during winter, but travelled increasingly short distances, which they attributed to climate change leading to fewer cold spells during more recent years.

The Mallard is a partial migrant in most of western Europe, with resident breeding birds being supplemented by migrants during the winter (Young 2005). This is the case of the population wintering in Camargue, which originates from the *c.* 5,000 local breeding pairs (Olioso 2009) supplemented by migrants from northern areas and countries (Tamisier & Dehorter 1999). There is no precise monitoring of the Camargue breeding population, but it is considered to have been stable in recent decades (Olioso 2009). The wintering population, which is monitored much more rigorously, showed no significant trend during the late 20th century (years 1964–2002 inclusive), with a mean number of *c.* 18,000 individuals (Tamisier 2004). However, these numbers have increased dramatically over the more recent 1984–2002 period. This has been especially the case for September counts (+27%), likely reflecting the development of releases of captive-bred Mallard for hunting purposes (Tamisier 2004), which occur during the summer. Again, there is no precise count of the number of such birds being released in the Camargue annually, but the most recent estimates suggest *c.* 50,000 individuals are released before the hunting season each year (Champagnon 2011), while the practice was considered virtually non-existent before the mid-1970s. Captive-bred Mallard released for hunting have poor or no migratory abilities (with only a few hundred meters between release and recovery site reported in Champagnon 2011; see Söderquist 2015 for a review), so the increase in this practice of releasing Mallard in Europe since the 1970s and subsequent genetic hybridization among wild and captive-bred conspecifics (Čížková *et al.* 2012; Champagnon *et al.* 2013) may have led to an increasingly sedentary behaviour in this population (Söderquist 2015).

In addition to the above potential changes in the composition of wintering Mallard populations in the Camargue, local habitat management practices have also changed over the last decades (Brochet *et al.* 2012), which may affect the habitat use and

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distribution of birds at the flyway scale. For instance, an earlier study has shown that changes in Camargue habitat management have increased attractiveness of the region for migratory Eurasian Teal *Anas crecca* (Guillemain *et al.* 2015).

This paper aims to determine whether the recovery locations of Mallard ringed in Camargue during winter have changed over the last 50 years, analogous to the change in movements recorded for the species in other parts of Europe. It also proposes explanatory hypotheses for potential changes, new avenues for research on the composition of duck populations and possible changes in the migration strategies and geographic distribution of Mallard in Europe over time.

Methods

Recovery data recorded for 11,453 Mallard ringed in Tour du Valat, Camargue (43°30'N, 4°40'E) between 28 March 1950 and 17 January 1978, hereafter termed "historical Camargue data", and 1,789 Mallards ringed in the same region in the Marais du Vigueirat (43°31'N, 4°47'E) between 5 December 2002 and 5 December 2013 (hereafter "modern Camargue data") were analysed to determine any changes in recovery distances since the mid 20th century. To control for a change in hunting reporting rates between historical and modern dataset, we also studied the recovery locations of Mallard ringed over the recent years in the Bassin Parisien, northern France. Data for the Bassin Parisien came from 1,292 Mallard ringed in Arrigny (Marne department, 48°37'N, 4°42'E), Outines (Marne, 48°33'N, 4°39'E), Marolles-sur-Seine (Seine et Marne, 48°23'N, 3°02'E), Moutiers-en-Puisaye (Seine et Marne, 47°37'N, 3°11'E), Noyen-sur-Seine (Seine et Marne, 48°27'N, 3°21'E), Saint-Julien-du-Sault (Yonne, 48°02'N, 3°18'E) and Vergigny (Yonne, 47°58'N, 3°43'E), all ≤ 180 km to the south-east of Paris, between 16 September 2005 and 5 March 2015. From each study area, only individuals ringed between September and March were considered, restricting the analysis to birds that were already flying at ringing. We also used only ring recoveries of dead birds in the analyses (*i.e.* not live recaptures or re-sightings, of which there were only a handful away from the ringing site in the historical dataset). The cause of death was known for 1,726 (92.3%) of the recoveries. Of these, 88.9% were shot by hunters in the historical Camargue dataset, 93.8% in the modern Camargue dataset and 97.5% in the modern Bassin Parisien dataset; differences between time periods and sites in the proportion of birds found shot were not significantly different (all pair-wise Chi-squared tests: $\chi^2_1 < 0.48$, all $P > 0.83$, n.s. in each case). The other sources of mortality, which included birds caught in traps or nets, mortality at ringing and predators, therefore had marginal influence on the recovery data.

We plotted the recovery locations of the birds, and compared the mean latitude, longitude and recovery distance using non-parametric Mann-Whitney and Kruskal-Wallis tests in Statistica 10 (Statsoft 2011) because the residuals of preliminary ANOVAs were not normally distributed (Kolmogorov-Smirnov tests: all $P < 0.01$) and different forms of transformation failed to solve this problem. Because the hunting

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seasons in European countries including France have shortened considerably since the 1950s (see Figure 9.8 in Guillemain & Elmberg 2014), an observed shorter recovery distance over time periods could be the consequence of fewer recoveries during spring migration in the modern dataset. The barycentre of the recoveries (mean latitude and mean longitude for all individuals from a ringing area during the historical or modern periods) and the mean recovery distances were thus computed both on considering all recoveries throughout the year and also when considering only recoveries made during the more restricted current hunting season, *i.e.* September–January inclusive.

A change in the median date of ringing within the winter between the historical and the modern years could lead to different exposure times to hunting, which in turn could result in a differential probability of the bird being recovered locally in the Camargue. Specifically, if the timing of ringing shifted to earlier periods in the autumn and winter, then a longer exposure to hunting at the Camargue wintering site and consequently shorter ring recovery distances would be expected. We therefore also compared within-winter ringing dates for the historical and modern Camargue birds. The first of January was calculated as day 0, with days from September to December each year having negative values (Guillemain *et al.* 2013).

An earlier study of ring recovery distance in Mallard found that first-year birds were recovered at greater distances than adults (*i.e.* after-hatch year birds) during the later stage of the first winter (January–February; Sauter *et al.* 2010). Because there were relatively few recovery data for Mallard ringed in recent years (*i.e.* in the modern datasets) we had to consider all recoveries in the analyses presented here, including those made after the year of ringing (*i.e.* combining the intra- and inter-annual recoveries). Only two age classes can be distinguished in dabbling ducks (first-year *vs.* after-hatch year individuals; *e.g.* Mouronval 2014), age at ringing may differ from age at recovery, and the recovery data were grouped into just two categories (historic and modern recoveries), so we did not attempt to test for any age differences in the distance travelled. Sauter *et al.* (2010) did not find any difference between the sexes in ring recovery distance for Mallard, but an earlier study of Eurasian Teal ringed in the Camargue showed that males generally move further afield than females (Guillemain *et al.* 2005). Within each period and ringing area we therefore compared the mean recovery distance between sexes, and also tested for temporal changes in recovery distance from the Camargue between time periods separately for males and for females. It should be noted that sex was not recorded for three of the historical Camargue Mallard on ringing.

Results

From a total of 14,534 ringed Mallard included in the study, we obtained 1,622 recoveries of historical Camargue birds from Tour du Valat (14.2% of the ringed birds from this period and area), 128 recoveries of modern Camargue birds from Marais du Vigueirat (7.1%) and 120 recoveries of modern Bassin Parisien

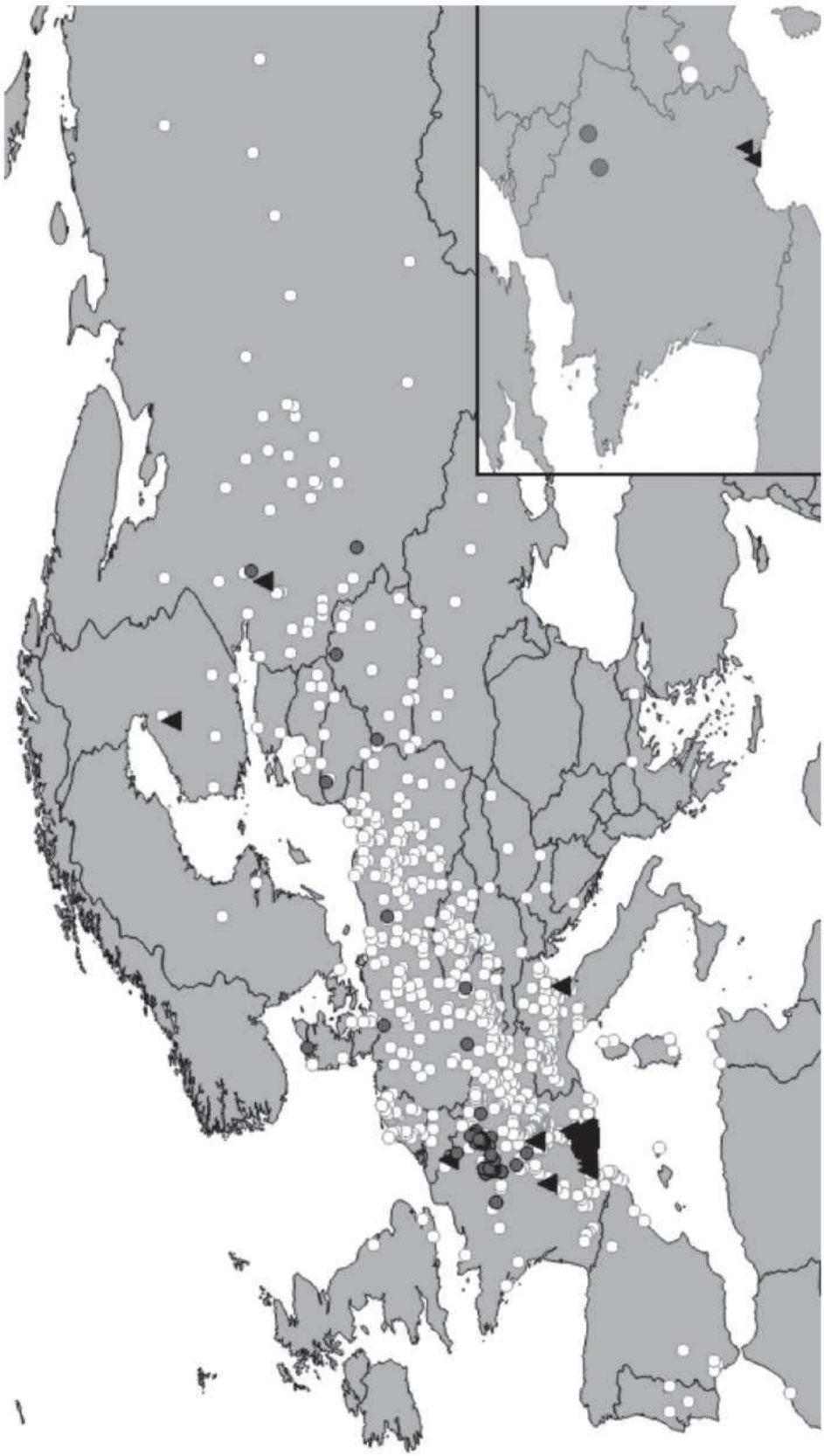

Figure 1. Recoveries of Mallard ringed in Camargue from 1950 to 1978 (white dots, "historical Camargue"), in Camargue from 2002 to 2013 (black triangles, "modern Camargue") and in the Bassin Parisien from 2005 to 2015 (grey dots). The small map to the bottom right shows the barycentre of the recoveries for each of these ringing areas and periods, depending on whether recoveries over the whole year or only from September–January were considered. The barycentre in the later case is consistently further to the southwest.

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individuals (9.3%). The median ringing date of these birds was day –5 (*i.e.* 27 December, range = days –151 to +89, n = 1,622) for the historical Camargue dataset, and day 10.5 (*i.e.* 11 January, range = days –52 to +72, n = 128) for modern Camargue birds, which was significantly different (Mann-Whitney U-test: Z = –5.00, $P < 0.0001$).

Figure 1, which illustrates the ring recovery locations of birds from each ringing area and time period, shows that the historical Camargue birds were recovered throughout Europe, clearly delineating their flyway from southern France to western Russia across the Netherlands, Switzerland, northern Italy, Germany, Poland and the Baltic countries. Although less numerous, foreign recoveries in these countries were also obtained for the modern Mallard from the Bassin Parisien. Conversely, very few modern Camargue Mallard were recovered outside France, albeit this was technically possible since some Camargue birds were recently recovered in Finland (n = 1) and Russia (n = 1), > 2,500 km away. The mean latitude of recoveries was significantly lower in the modern than in the historical Camargue dataset (Mann-Whitney U test: Z = 7.19, $P < 0.0001$), while the mean longitude was just at the significance threshold (Z = 1.91, P = 0.057). This led to the barycentre of recoveries being much closer to the ringing site during modern than historical years, both when the whole year or when only September–January recoveries were considered (Fig. 1). The mean recovery distance differed between the three ringing areas and periods; historical Camargue: 416.6 km (s.e. ± 17.4, n = 1,622); modern Camargue: 74.1 km (s.e. ± 28.9, n = 128); modern Bassin Parisien: 126.0 km (s.e. ± 35.6, n = 120) (Kruskal-Wallis: $H_{2,1870}$ = 65.47, $P < 0.0001$; Fig. 2). Multiple bilateral comparisons at $P < 0.05$ indicated that such differences were due to a greater recovery distance for the historical Camargue Mallard than in the two modern datasets, which did not differ significantly from each other (Fig. 2a). If only the recoveries between September and January were considered, the mean distances were slightly lower, but the differences between ringing sites and periods remained similar ($H_{2,1184}$ = 57.23, $P < 0.0001$, Fig. 2b), although this time all three mean values differed from each other in multiple pairwise comparisons.

The comparison of ring recovery distances between sexes yielded non-significant results in the modern datasets (recoveries around the year considered; Camargue: Z = 0.03, P = 0.98; Bassin Parisien: Z = –0.80, P = 0.42, n.s. in each case), while in the historical Camargue dataset females were recovered further away than males (495.3 km, s.e. ± 30.0, n = 599 and 364.7 km, s.e. ± 20.7, n = 1,020, respectively; Z = 3.60, P = 0.0003). The reduction in ring recovery distance of Camargue-ringed Mallard was apparent both in males (mean modern recovery distance = 58.6 km, s.e. ± 25.3, n = 106; Z = 3.59, P = 0.0003) and in females (mean modern recovery distance = 148.7 km, s.e. ± 116.6, n = 22; Z = 2.41, P = 0.02).

Discussion

The recovery distance of Mallard ringed in Camargue during winter has shortened considerably over the last 50 years, declining from a mean of 417 km between the 1950s

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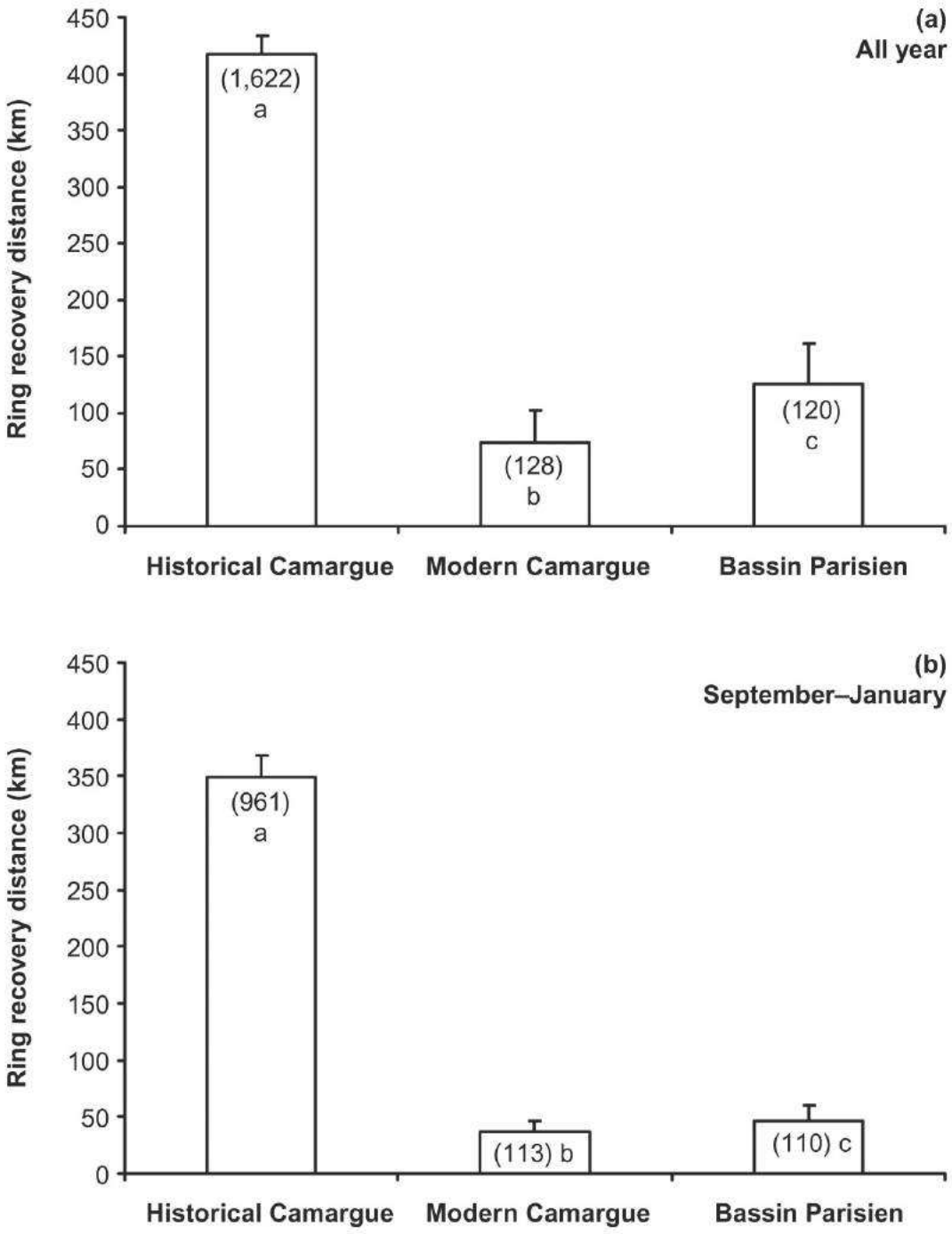

Figure 2. Mean recovery distance for Mallard ringed in Camargue from 1950–1978 ("historical Camargue"), in Camargue from 2002–2013 ("modern Camargue") and in the Bassin Parisien from 2005–2015. The top graph comprises all recoveries any time during the year, while the bottom graph is restricted to recoveries made from September–January inclusive. In both cases the mean value for historical Camargue Mallard was significantly greater than in the two other areas/periods (see text). Numbers in brackets are sample sizes, *i.e.* number of ring recoveries. Columns with different letters differed significantly in multiple pair-wise comparisons. Vertical bars show standard errors.

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and 1970s to 74 km in more modern times. The decline in the ring recovery distance suggests that our sample of Camargue-wintering Mallard is increasingly composed of resident and short-distance migratory birds. The present recovery distance of Camargue-ringed Mallard is comparable to the 56 km for Mallard ringed in Great Britain or the 61 km in Italy in Sauter *et al.* (2010, note however that movements of < 5km were omitted from this later study), as well as being comparable although lower than the mean of 126 km for ducks ringed in the Bassin Parisien described here. Actually, 88% of the modern Camargue Mallard were recovered < 50 km from their ringing site, while this proportion was only 56% in the historical dataset. Several hypotheses could be put forward to explain such a pattern, as described below.

Methodological issues

First, it cannot be completely excluded that hunting pressure and reporting rates of ringed birds have changed at different rates in different parts of Europe. General hunting pressure and/or ring reporting rates have declined over time, resulting in the declining percentage of rings lately recovered, here and elsewhere (*e.g.* recovery rates for waterfowl ringed in Britain and Ireland have halved from *c.* 0.14 in the 1960s to 0.07 in the 1990s, Robinson *et al.* 2009). A differential rate of decline in hunting and/or reporting rates in different parts of the flyway therefore could have caused an apparent shift in the distribution of ring recoveries, as already acknowledged by Sauter *et al.* (2010), Gunnarsson *et al.* (2012) and Guillemain *et al.* (2015) for ducks. However, the Bassin Parisien results described in the current study show that French-ringed birds may still technically be recovered and reported from other countries. Moreover, the Camargue results suggest increasing proportions of recoveries to the south, while in contrast Sauter *et al.* (2010) and Gunnarsson *et al.* (2012) recorded increasing recoveries in northern areas. If local hunting pressure in and around the Camargue had increased sufficiently to bias the results towards more local recoveries, a similar shift of the recoveries towards the Camargue should also have been apparent for the Swiss Mallard studied by Sauter *et al.* (2010), since some of the Swiss ducks also wintered in southern France. There is therefore no indication that ring reporting probability has changed at different rates in different parts of the flyway, and should thus bias the results significantly in any of the Mallard studies listed above, nor the present one. Similarly, the current results for Camargue-ringed Mallard cannot be attributed to the general shortening of the hunting seasons in France and in other countries, since we obtained similar results when considering recoveries made only during the period of the current hunting season, *i.e.* September to January. Finally, there was a difference between historical and modern Camargue Mallard in the date on which birds were ringed during the winter, which could have affected their exposure to local hunting, and hence potentially their ring recovery distance. The historical birds were ringed slightly earlier than modern ones (late December *vs.* early January), however, resulting in them being exposed for longer

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periods to local hunting, yet they were recovered further away from the ringing area.

Change in Camargue habitats

A second hypothesis could be that the habitat conditions have become so good for dabbling ducks in the Camargue that individuals formerly migrating from northern countries have become year-round residents, or arrive earlier during the season and spend more time in the area nowadays. An earlier study has shown that Eurasian Teal have become increasingly faithful to the Camargue as a winter quarter, likely owing to changes in water management making the wetlands more permanent and plant-productive than they once were, in addition to the large quantities of bait now being spread in some hunting estates (Guillemain *et al.* 2015). In the same way that such practices seem to attract Eurasian Teal from one winter to the next, they could also lead the Mallard discovering this region to remain in the area around the year to a greater extent than they did in the past. This is again highly unlikely, however, because dabbling duck females are strongly philopatric, returning year after year to the same breeding area (Oring & Sayler 1992; Blums *et al.* 1996). Our historical Camargue dataset showed that females apparently came from more distant sites than males; hence, many of these were true migrating birds. It seems very unlikely that changes in local habitat conditions in the Camargue would have been large enough to lead dabbling duck females to completely forego their philopatric habits. Furthermore, if this had been the case the local breeding population would have increased significantly. Although the monitoring of Camargue breeding ducks is poor, such a massive change would likely have been detected, whereas the breeding population is conversely considered to have been relatively stable over the last decades (Olioso 2009).

Climate change

Because the number of local breeding birds had not increased dramatically between the 1950s–1970s and more recent years (see above), such a pattern could have been due to a decline of the Nordic breeding populations, producing fewer migrants to fuel the Camargue wintering groups within which catching occurred, hence gradually leading to a greater share of local birds in the ringing sample. The most recent breeding population estimates do suggest long-term declines in countries with large Mallard breeding populations, such as the Netherlands, Lithuania, Estonia or Ukraine, but other countries important for this species such as Latvia, Poland or Germany show no trend or an increase in their populations, and the changes in the number of Russian breeding Mallards are simply unknown (Birdlife International 2015). It is therefore not possible at present to determine if the declining recovery distance of Camargue-ringed birds can be attributed to changes in abundance in different breeding areas across Europe and into Russia. What is likely, however, is that northern migrant Mallard increasingly forego long migrations to distant Camargue winter quarters (winter short-stopping, *sensu* Elmberg *et al.* 2014). Gunnarsson *et al.*

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(2012) and Sauter *et al.* (2010) both found that Mallard were recovered at increasingly shorter distances from the ringing site over time. Gunnarsson *et al.* (2012) studied ducks ringed in Sweden, while Sauter *et al.* (2010) used ringing data from a variety of European countries (Great Britain, Denmark, Sweden, the Netherlands, Belgium, Germany, Switzerland and Italy) but not including France. In both cases, only winter recoveries were considered, and were consistently to the south or southwest of the ringing sites: shorter recovery distances therefore corresponded with recoveries gradually occurring further to the north and/or east, which Gunnarsson *et al.* (2012) attributed mainly to climate change leading to a general shift in the birds' wintering grounds. Sauter *et al.* (2010) considered this shift to be primarily a consequence of decreasing frequency of winter cold spells, resulting in Mallard being pushed less frequently to the southwest during winter. Both scenarios are consistent with our results because they would translate into fewer migrants from these areas within the Camargue wintering groups, hence a greater proportion of local birds wintering in southern France and consequently a shortening of their mean ring recovery distance.

Massive releases of captive-bred Mallard

The last hypothesis to explain such a shortening of the ring recovery distance is linked with the fact that the Mallard is the only duck species where releases of captive-bred birds are carried out for hunting purposes. This is practised at a massive scale in Europe, where an estimated 3 million individuals are released annually, of which 1.4 million are released in France alone (Champagnon 2011). Champagnon (2011) also estimated that *c.* 50,000 individuals are released annually in the Camargue, mostly during the summer, while this was virtually non-existent during the historical years of our study. Captive-bred birds usually do not disperse much (review in Söderquist 2015): the mean ring recovery distances of 861 released Mallards in Camargue were only 610 m in Champagnon (2011). It is possible that the winter catch for ringing in the Camargue is increasingly composed of these largely non-migrating released birds. Unfortunately, these birds are not marked and very much resemble their wild conspecifics in appearance, so the origin of an individual is impossible to tell when the bird is in the hand having been caught for ringing. Hybridization of the released Camargue Mallards with their wild conspecifics also does occur (Champagnon *et al.* 2013), and may have led the birds to remain in the Camargue throughout the year. Introgression of captive genes may lead to changes in migratory behaviour (Champagnon *et al.* 2012), as observed in different species of birds where wild populations were supplemented with more resident individuals, for instance Common Quail *Coturnix coturnix* (Derégnaucourt *et al.* 2005), Little Bustard *Tetrax tetrax* (Villers *et al.* 2010) or White Stork *Ciconia ciconia* (Massemin-Chalet *et al.* 2006).

Future research

Although the pattern of a decrease in the recovery distance for Mallard ringed in

Camargue during winter is very clear, it is not currently possible to tease apart the three main hypotheses proposed above (*i.e.* a change in attractiveness of Camargue habitats, a climate change effect, or the consequences of massive releases of captive-bred Mallard), which furthermore may not be mutually exclusive from each other. We suggest that a combination of genetic and isotope studies of wing feathers should be carried out while ringing Mallard in Camargue, along with testing museum specimens from a period corresponding to our historical data. This will provide an assessment of the proportion of birds produced locally while also determining whether they are of wild or captive origin. In addition to such laboratory approaches, annual surveys of the Mallard population breeding in this region would be very valuable, although unfortunately difficult and expensive to set up (Fouque *et al.* 2004; C. Tetrel, unpubl. data). Such information would help to quantify the relative proportion of sedentary birds in the population, which are likely responsible for the shortening of mean ring recovery distances in this species over the last 50 years, and determine whether such increased sedentarity is the consequence of bird releases.

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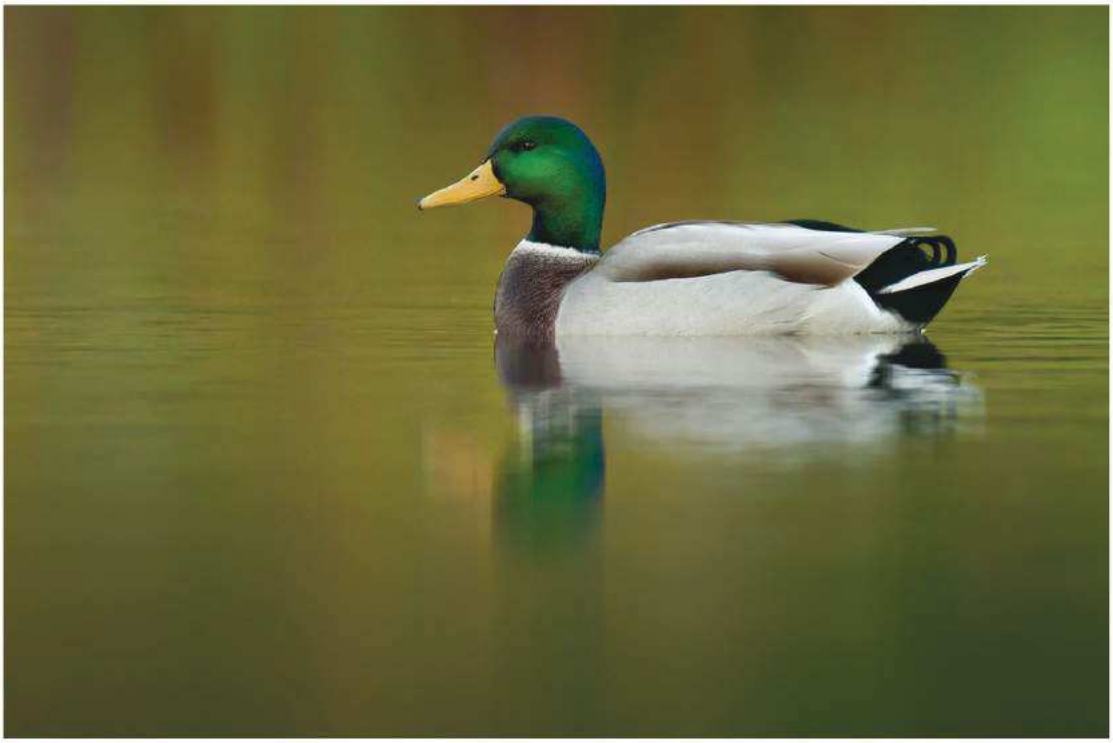

Photograph: Mallard, by Des Ong/FLPA.

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II. LIST OF SCIENTIFIC COMMUNICATIONS

II.1 Oral communications

Pernollet C.A., Cavallo F., Simpson D., Brogi A., Niang A., Gauthier-Clerc M. & Guillemain M. 2016. Winter flooding and use of rice fields by waterfowl in Europe: towards mutual benefits for ducks and farmers. *7th North American Duck Symposium, Annapolis, USA, 1-5 February 2016.*

Guillemain M., **Pernollet C.A.**, Arzel C., Elmberg J. & Eadie J.M.A. Foraging, nutrition, and energetics of waterfowl : a European perspective. Communication invitée, *7th North American Duck Symposium, Annapolis, USA, 1-5 February 2016*.

Guillemain M., Champagnon J., **Pernollet C.A.**, Devineau O., Elmberg J., Cavallo F. & Massez G. Combined effects of climate change and fluctuating habitat quality on the distribution of ducks in southern Europe. *7th North American Duck Symposium, Annapolis, USA, 1-5 February 2016.*

Pernollet C.A., Cavallo F., Simpson D., Brogi A., Niang A., Gauthier-Clerc M. & Guillemain M. 2015. Rice fields winter flooding for waterfowl in Europe: a management to be promoted? Communication invitee, *Wetlands in Agricultural Landscapes Conference, České Budějovice, Czech Republic, 11-16 October 2015.*

Guillemain M., Champagnon J., **Pernollet C.A.**, Elmberg J., Mouronval J.B. & Massez G. 2015. Still worth the trip ? Camargue Teal migration patterns, body condition and demographic parameters over 60 years. *4th Pan-European Duck Symposium, Hanko, Finland, 7-11 April 2015.*

Pernollet C.A., Gauthier-Clerc M. & Guillemain M. 2014. Rice farming and duck interactions : looking at possible mutual benefits by testing post-harvest practices and duck densities. *26th International Ornithological Congress, Tokyo, Japan, 18-24 August 2014.*

Pernollet C.A., Cavallo F., Guelmami A., Brogi A., Gauthier-Clerc M. & Guillemain M. 2014. To Flood, or Not to Flood: that is a European question. Ducks wintering in rice fields in Camargue. *2nd Conservation Sciences in the Mediterranean Region. Tour du Valat, Arles, France, 28-30 April 2014.*

Brogi A., **Pernollet C.A**, Gauthier-Clerc M. & Guillemain M. 2014. Waterfowl foraging in winter-flooded rice fields: impact on weeds and stubble. *2nd Conservation Sciences in the Mediterranean Region. Tour du Valat, Arles, France, 28-30 April 2014.*

Pernollet C.A., Guelmami A., Gauthier-Clerc M. & Guillemain M. 2013. Flooded fields and wintering ducks: a comparison of hosting potential among European rice production areas. *37th Annual Meeting of the Waterbirds Society, Wilhelmshaven, Germany, 24-28 September 2013.*

II.2 Posters

Brogi A., **Pernollet C.A.** & Guillemain M. 2014. Waterfowl foraging in winter-flooded rice fields : weed control and increased straw decomposition. *AREB, 10th Ecology and Behaviour Meeting, Montpellier, France, May 2014*.

Pernollet, C.A., Cavallo F., Gauthier-Clerc M., A.J. Green, J. Figuerola & Guillemain M. 2015. Nocturnal use of ricefields by ducks in two major winter winter quarters of Western Europe. *4th Pan-European Duck Symposium, Hanko, Finland, 7-11 April 2015.*

Pernollet, C.A., Gauthier-Clerc, M. & Guillemain, M. 2015. The use of rice fields by wintering ducks: searching for mutual benefits to ducks and farmers. *27th International Congress for Conservation Biology, Montpellier, France, 2-6 August 2015.*

Mallard ducks foraging in winter-flooded rice fields: Impact on weeds and stubbles

Anne Brogi[1], Claire Pernollet[1 2] & Matthieu Guillemain[1]
Contact: anne.brogi@gmail.com

Introduction

ASIA : Raising farming ducks in paddy rice is a **traditional agro-ecological practice**.

USA : As a post-harvest habitat management scheme, rice fields are flooded in winter to **attract waterfowl**.

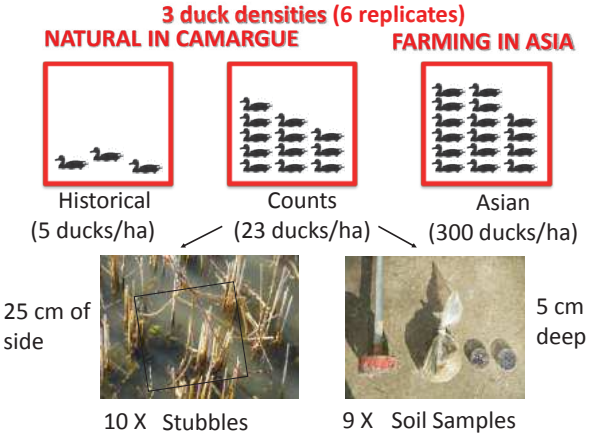
FRANCE : Winter flooding is poorly used in **Camargue** (7%) despite the **potential** for **providing nocturnal foraging habitat** for wintering ducks.

Can wintering ducks provide **agronomic benefits** to farmers?

- What is the effect of ducks trampling on **stubble** ?
- What is the effect of ducks on the **weed seed bank** ?

Methods: experimental tests on a flooded rice field

Representation of ducks foraging during the whole winter season in Camargue : 10h/night, 4 months (Nov-Feb)

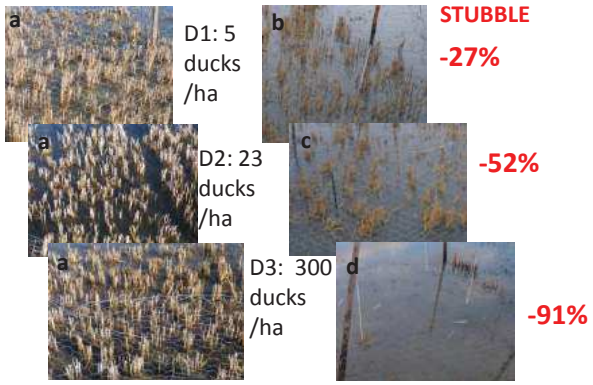


Measures taken before (Pre) and after (Post) duck tests

Results : Significant decrease of the stubble - Non significant decrease of the weeds seed bank

GLM (Poisson): Nber of stubbles ~ Treatment + Duck Density + Treatment * Duck Density + (1|Manipulation)

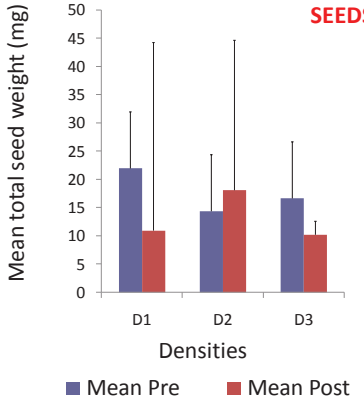
Significant effect on the stubble



a, b, c, and d show the significant differences

GLM (Gaussian): Total seed weight ~ Treatment + Duck Density + Treatment * Duck Density + (1|Manipulation)

Despite an apparent diminution of the seed bank, no significant effect on the seed weight



Apparent diminution:
D1: -50%
D3: -40%

Conclusions

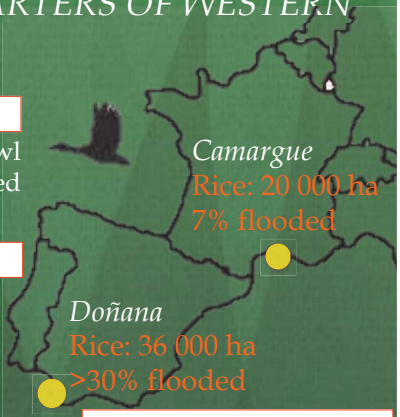
- Making rice fields available to waterfowl by winter-flooding could bring agronomic benefits to farmers through increased straw submersion for better decomposition.
- However, the ducks did not decrease the seed bank significantly. Their effect was probably masked by the high variability of the seed distribution in the field.

1 Office National de la Chasse et de la Faune Sauvage, CNERA Avifaune Migratrice, France
2 Centre de Recherche de La Tour du Valat, Arles, France

NOCTURNAL USE *OF RICEFIELDS BY DUCKS IN TWO MAJOR WINTER QUARTERS OF WESTERN EUROPE*

INTRODUCTION

European ricefields provide nocturnal foraging habitat to waterfowl during winter. However, few nocturnal survey counts have been carried out (to properly quantify this pattern).



STUDY SITES DIFFERENCES

Camargue (France) : tradition of burning-mowing, limited use of winter flooding (7%) a relatively stable offer of daily roosting sites close to ricefields.

Doñana (Spain) extensive use of winter flooding (>30%). Two main daily roosting sites, natural roosting and foraging wetlands in the National Park being dry at the moment of the survey.

NOCTURNAL SURVEYS

Camargue : Nov 2013 to Feb 2014, 51 fields in 9 farms surveyed, survey repeated weekly.

Doñana : Nov 2014, 136 fields surveyed, 25 transects, 3 transects per night, 2 to 5 fields in each transect.

NIGHT SURVEY: DUCK SPECIES USING RICEFIELDS

Ducks in ricefields in Camargue

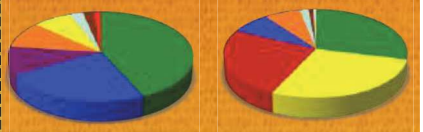
Ducks in ricefields in Doñana

Mallard · Pintail · Shoveler · Teal · Gadwall · Wigeon

Mallard, Teal, Pintail observed in the ricefields in Camargue
Mallard, Shoveler, Wigeon commonly observed in Doñana

DIURNAL SURVEY IN ALL HABITATS

Aerial count duck community, same period

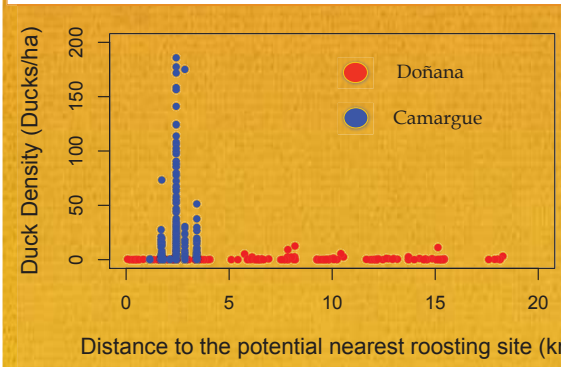


Red Crested Pochard · Common Pochard · Shelduck

Ducks Community in Camargue

Ducks Community in Doñana

DUCK DENSITIES & POTENTIAL MOVEMENTS



High concentration of ducks in Camargue in the few flooded ricefields compare to Doñana.

Ducks potentially fly much more from their diurnal roosting to their nocturnal foraging site in Doñana than in Camargue.

DUCKS & HABITAT VARIABLES

Best GLMM & Post-Hoc Tukey Test

Ducks~ Straw Management ** + Nearest Roost ** (0.90 positive)

Doñana → Stubble – Mudflat -1.44 **

Ducks~ Straw Management *** + Water Depth*** + Nearest Roost

Camargue → Ploughed – Mudflat -5.30 ***
Stubble – Mudflat -2.47 *
High – Dry 3.02 ***
Low – Dry 1.80 *
Middle – Dry 2.20 **

Camargue: More ducks in flooded ricefields

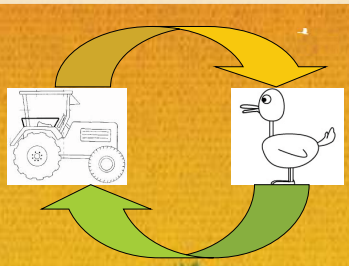
Claire A. Pernollet, François Cavallo, Michel Gauthier-Clerc, Jordi Figuerola, Andy J. Green, Matthieu Guillemain

Email: claire.pernollet@oncfs.gouv.fr

The use of rice fields by wintering ducks: searching for mutual benefits to ducks and farmers

INTRODUCTION

Winter flooding has been identified as the best waterfowl-friendly management in post-harvest ricefields in the U.S., providing mutual benefits to wintering ducks through its direct translation into foraging grounds, and to farmers through improved straw decomposition rate and weed seeds reduction.



We tested for such mutual relationship in Europe via 4 distinct studies.

QUESTIONS & METHODS

Winter post-harvest practices in Europe & Duck use – Empirical tests

1) Do rice field winter flooding areas in Europe explain the number of ducks ? Satellite images analysis & Wetlands International duck survey data

2) Do post-harvest practices in ricefields influence seed availability and nocturnal duck use in France? Seed core samples & nocturnal duck survey

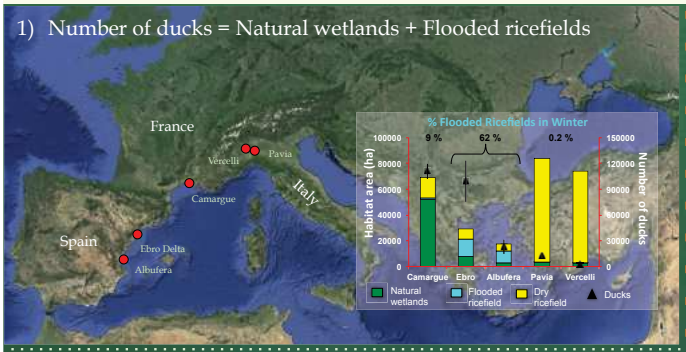
Potential agronomic benefits of rice field winter flooding & duck attraction – Experimental tests

3) Do wintering ducks have an effect on straw trampling and seed bank in flooded fields? Wing clipped mallards, stalk counts, soil core samples

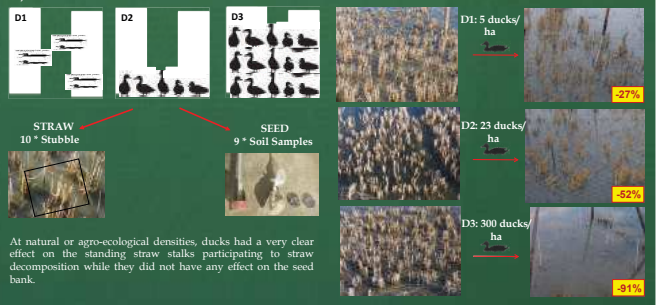
4) Is weed seed deterioration different in flooded vs. dry rice fields? Greenhouse test with 4 plant species : biomass loss, seed viability, germination across winter

RESULTS

1) Number of ducks = Natural wetlands + Flooded ricefields



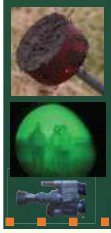
3) Ducks reduce straw but not weed seeds

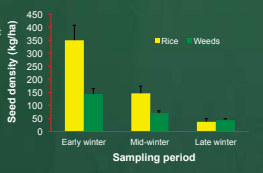


At natural or agro-ecological densities, ducks had a very clear effect on the standing straw stalks participating to straw decomposition while they did not have any effect on the seed bank.

2.1) Ploughing reduces seed availability
2.2) Ducks are more numerous in flooded ricefields

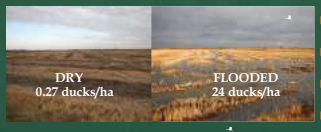
Mean seed availability does not dependent on straw management (burning, chopping or disking) .

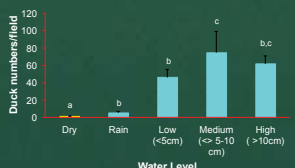




Seed depletion rate was highly dependent on initial seed density, and was greater with ploughing (stat not shown).

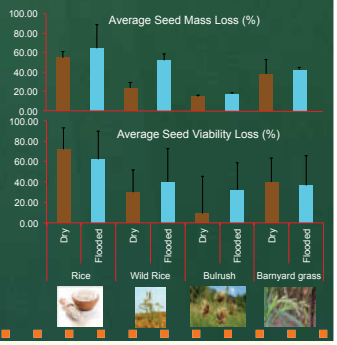
Winter flooding did not significantly affect seed depletion rate AND makes seeds available for wintering ducks even only with rainÂ





4) Seed deterioration varies among species & dry/flooded conditions

Cultivated rice is the species with the biggest degradation whatever the ricefield condition was. Winter ricefield flooding is known to act as biological weed control for wild rice.



CONCLUSION

Flooding ricefields after harvest would therefore provide nocturnal foraging habitats to ducks, and also bring agronomic benefits in terms of increased straw decomposition and reduction of the weed seed bank. Winter flooding of ricefields in Europe would hence benefit both farmers and wintering waterfowl, and should be promoted by adequate agro-environmental policy wherever possible.

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Office National de la Chasse et de la Faune Sauvage

TOUR DU VALAT

II. LIST OF POPULAR COMMUNICATIONS

II.1 Oral communications

September 2015: Oral presentation at the annual meeting of the rice farmers, French Rice Centre, Arles, France.

June 2013-July 2015: Oral presentation to the Agriculture Committee of the Camargue Regional Natural Park, Arles, France.

May 2013-2014-2015: Organization and communication at the annual meeting of Camargue habitat managers, hunters and farmers. Tour du Valat, Arles, France.

January 2015: Lecture for the course *Topics in Avian Ecology and Management for BSc students in Biology* and presentation for the USGS Dixon team: "*Torrent ducks in Chile, Rock Alpine Ptarmigan in the Swiss/French Alps, and dabbling ducks in French rice fields*". Davis, California, United-States.

May 2013-May 2014: Organization committee of the European Conference for young researchers "*10th Ecology and Behaviour Meeting*". Leader of the Conservation and Behaviour session. Montpellier, France.

June 2013: Participation and oral communication to the European Life Project 09/NAT/IT/000093 EcoRice on the biodiversity in rice fields. Vercelli, Italy.

February 2013: Oral presentation on the PhD project to the Wildfowl and Wetlands Trust. Slimbridge, UK.

Pictures of several meetings: Vercelli, Tour du Valat, French Rice Centre

II.2 Grey literature

Pernollet C.A. 2015. Quina importància tenen els arrossars inundats a l'hivern per a les anàtides a Europa? *Soldó 44*. Informatiu del Parc Natural del Delta de l'Ebre. Parc Natural del Delta de l'Ebre, Generalitat de Catalunya http://parcsnaturals.gencat.cat/ca/delta-ebre/coneix-nos/centre- (in Catalan).

Tesio F., Nobile S., **Pernollet C.A.** 2015. La sommersione invernale può mettere d'accordo risicoltori, anatre, ambientalisti e birdwatchers! *Natura e montagna*. Anno LXII – 2, 7-11 (in Italian)

Popularization leaftlet in French, Spanish and Italian for farmers on the results of **Article 2**.

Popularization leaftlet in French on the results of **Article 5.**

C. Pernollet

Paisatge hivernal d'arrossars a la Camarga (França).

Quina importància tenen els arrossars inundats a l'hivern per a les anàtides a Europa?

Un estudi recent, publicat pel Centre de Recerca de la Tour du Valat i per l'Oficina Nacional de la Caça i la Fauna Salvatge (França) a la revista científica Biological Conservation, ha avaluat per primera vegada la relació entre la inundació hivernal als arrossars i l'abundància d'ànecs, en cinc grans paisatges arrossaires de tres països europeus.

Claire Pernollet

CNERA Avifaune Migratrice, Office National de la Chasse et de la Faune Sauvage
La Tour du Valat (França)

Les àrees agrícoles ofereixen, sota determinades condicions, hàbitats idonis per als ocells al llarg de tot o part del seu cicle vital (reproducció, migració i hivernada). Si les pràctiques agronòmiques després de la collita són adequades, els arrossars poden esdevindre, a l'hivern, espais d'alimentació molt importants per als ocells aquàtics (anàtides, ardeids, limícoles...). Per exemple, moltes anàtides que passen el dia descansant en espais tranquils (llacunes litorals, aiguamolls, salines..), sovint formant grans estols, es desplacen a la nit per alimentar-se als arrossars, en algunes zones atrets per l'aliment que s'aporta artificialment a les zones cinegètiques.

Tot i que aquesta relació entre superfície inundada (arrossars i aiguamolls naturals) i abundància d'ànecs es coneixia de fa anys, mai no s'havia avaluat amb detall i a una escala geogràfica gran. I, més particularment, l'efecte que ha tingut a llarg termini la implementació de la inundació hivernal com a mesura agroambiental (iniciada a començaments dels anys 2000), al delta de l'Ebre i l'albufera de València sobre el contingent d'ànecs.

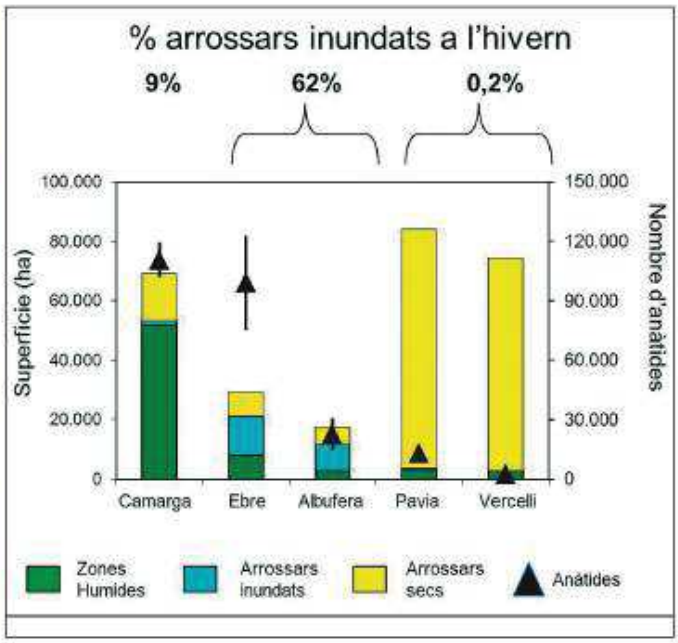
Aquest estudi s'ha portat a terme en tres fases:

1. Mesura, mitjançant l'anàlisi d'imatges satèl·lit (2002-2012), de les superfícies de les zones humides naturals, i dels arrossars secs i inundats a l'hivern, a la Camarga (França), a les províncies de Vercelli i de Pavia a la vall del Po (Itàlia), així com al delta de l'Ebre i a l'albufera de València.
2. En una segona fase, s'analitzà numèricament el vincle entre aquestes superfícies i el nombre d'ànecs a l'hivern, obtingut a partir dels recomptes anuals d'ocells aquàtics al gener (IWC), coordinats per Wetlands International.
3. En la darrera fase es comparà estadísticament les tendències del nombre d'ànecs abans i després de la implementació de la mesura agroambiental d'inundació hivernal dels arrossars al delta de l'Ebre i l'albufera de València, que són les úniques regions arrossaires que han rebut fins ara un ajut financer que fomenten aquesta pràctica.

Els resultats d'aquest estudi indiquen que, en termes generals, l'abundància d'ànecs que passen l'hivern en aquestes regions està associada de manera positiva a la superfície de zones humides en sentit ampli, és a dir, comprenent tant les zones naturals com els arrossars inundats. Si es comparen els paisatges dos a dos, la Camarga i el delta de l'Ebre acullen aproximadament el mateix nombre d'ànecs, presentant la Camarga la superfície més gran de zones humides naturals i només el 9% dels seus arrossars inundats a l'hivern, mentre que al Delta el 62% dels arrossars es troben inundats –els hiverns considerats en l'estudi inclouen els anys amb assecaments hivernals com a mesura de lluita contra el caragol maçana– i la superfície de les zones humides naturals és molt més minsa. L'efecte de la inundació hivernal (62% dels arrossars) és menys patent a l'albufera de València, regió que presenta una zona humida natural central de mala qualitat. No obstant això, i tot i presentar una superfície global molt més reduïda que les altres regions estudiades, acull més ànecs que les dos àrees italianes, en les que gairebé la totalitat dels arrossars (els més vastos d'Europa) es mantenen eixuts a l'hivern. En l'àmbit europeu estudiat, els arrossars inundats actuen, doncs, com a complement de les zones humides naturals, ja que ofereixen a l'hivern un hàbitat d'alimentació nocturna adequat per als ocells aquàtics.

Des de la implementació de la

(continua a la pàgina següent)



M. Gauthier-Clerc

A l'esquerra, paisatge arrossaire hivernal a Doñana (rostolls inundats amb grans grups de cigonya blanca (*Ciconia ciconia*) i de capó reial (*Plegadis falcinellus*). A la dreta, composició de l'hàbitat de les àrees estudiades: zones humides, arrossars inundats i arrossars secs (mitjana del periode 2002-2012) i abundància hivernal d'ànecs de superficie (mitjana i error estàndard dels censos hivernals de gener, 2002-2012) en 5 de les principals àrees arrossaires d'Europa.

(ve de la pàgina anterior)

inundació hivernal dels arrossars com a mesura agroambiental (començaments dels anys 2000), els efectius d'ànecs a l'hivern a les dos regions de l'Estat espanyol han augmentat significativament, amb increments del 6-12% durant aquest període, mentre que les tendències eren negatives abans de l'aplicació d'aquesta mesura agroambiental. A la resta de zones considerades en aquest estudi (Camarga, vall del Po) no s'aplica aquesta mesura i els pocs arrossars inundats tenen només finalitats cinegètiques. Aquests resultats científics demostren l'interès que té la inundació hivernal dels arrossars per a les poblacions d'ànecs que es reprodueixen al centre i nord d'Europa, i que hivernen i migren emprant les regions arrossaires mediterrànies. Administrar de manera alternativa aquests espais agrícoles durant l'hivern per tal d'oferir, mitjançant la inundació, hàbitats d'alimentació complementaris a les zones humides naturals, procuraria un benefici important per als ànecs que hivernen i migren al voltant de la Mediterrània. En un moment en què s'està revisant i començant a aplicar el nou cicle de la Política Agrícola Comuna (PAC 2015), aquestes dades posen de manifest l'eficàcia d'una pràctica cultural per a la biodiversitat de certs paisatges arrossaires de la Unió Europea.

Un exemple a seguir a Europa?

Aquests resultats ofereixen un element a tindre en compte per reflexionar sobre les pròximes revisions de la Política Agrària Comuna de la UE. Això és encara més necessari en la mesura que aquesta mesura agroambiental es troba en perill de desaparèixer a l'Estat espanyol i que ni tan sols es planteja en altres països arrossaires de la Unió Europea. Tenint en compte aquests resultats, dos qüestions mereixen ser aprofundides. Què passaria si s'inundessen els arrossars a les regions de la vall del Po, a Itàlia, on les zones humides naturals han desaparegut gairebé? I a la Camarga, on les zones humides naturals són les més ben conservades? Quines conseqüències tindrà l'aturada de la subvenció de la inundació hivernal, des del 2013, a l'albufera de València? Algunes anàlisis que es troben en curs a la Camarga demostren que la inundació hivernal aportaria, a més a més, beneficis agronòmics (descomposició de la palla més eficient, lluita contra algunes males herbes) i que podrien servir d'arguments a favor d'aquesta pràctica.

D'altra banda, l'aplicació de la inundació hivernal als arrossars al delta de l'Ebre en els darrers anys s'ha vist molt condicionada per l'assecament de gran extensions d'arrossars a l'hemidelta nord com a mètode de lluita contra el caragol maçana (*Pomacea sp*). En el període hivernal de 2011-2014, la superficie d'arrossars eixuta ha variat entre el 24 i el 43%, exceptuant el 2013, durant el qual no s'aplicà aquest mètode de lluita. Alguns resultats preliminars semblen indicar que durant aquests hiverns no s'han apreciat canvis dràstics en la majoria de poblacions d'ocells aquàtics (particularment en els ànecs), per bé que el període ha estat curt i no es poden extraure encara conclusions significatives.

PER SABER-NE MÉS...

Pernollet C.A., Guelmami A., Green A.J., Curcó Masip A., Dies B., Bogliani G., Tesio F., Brogi A., Gauthier-Clerc M., Guillemain M. 2015. *A comparison of wintering duck numbers among European rice production areas with contrasting flooding regimes.* Biological Conservation 186: 214-224. DOI: 10.1016/j.biocon.2015.03.019

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La sommersione invernale delle risaie può mettere d'accordo risicoltori, ardeidi, ambientalisti e birdwatcher!

Tutto era cominciato dalla paglia di riso

Uno tra i problemi più complessi che devono affrontare i risicoltori nella gestione delle risaie è lo smaltimento della paglia di riso. Questa, infatti, ad alto contenuto siliceo rispetto ad altri tipi di paglie, è particolarmente resistente alla degradazione e, per il buon esito e la produttività di una coltivazione di riso, soprattutto nel caso di una monocultura, questo processo è fondamentale. La paglia non degradata, infatti, fermenta e produce gas che ostacolano lo sviluppo della pianta; inoltre, durante l'usuale sommersione estiva della risaia, il galleggiamento delle paglie non degradatesi nel corso dell'inverno-primavera ostacola il passaggio della luce, necessario alla crescita della pianta stessa.
Tradizionalmente, quando le aziende agricole non erano specializzate nella coltura del riso ma diversificavano le attività dedicandosi tra l'altro anche all'allevamento, le paglie venivano raccolte e utilizzate per le lettiere degli animali; in altri casi, invece, era consuetudine bruciare tutti i residui colturali (Fig. 1).

Tale tecnica era certamente semplice e poco dispendiosa; i roghi però avevano - e hanno - effetti collaterali piuttosto negativi, sia da un punto di vista della qualità dell'aria sia per ciò che riguarda la composizione del terreno e la sopravvivenza delle rane non ancora in letargo e ben infossate nel terreno. Questo, senza l'apporto della sostanza organica derivante dalla degradazione della paglia, risulta nel tempo impoverito.
In California, zona molto risicola, fino agli anni Ottanta del secolo scorso la bruciatura delle paglie era diffusamente praticata e provocava evidenti danni ambientali. Per contrastare gli effetti di questa tecnica sulla qualità dell'aria, nel 1991 fu emanato il "*Rice straw burning act*", una legge che imponeva gradualmente il divieto di bruciatura delle paglie nell'intera Sacramento Valley. Per i risicoltori divenne quindi necessario trovare nuove soluzioni per eliminare i residui colturali.
Alcuni imprenditori agricoli, pertanto, anziché asportare le ingenti masse di paglia prodotte, scelsero di lasciarle in campo e di allagare nuovamente le camere per far macerare le paglie che sarebbero poi state interrate con l'arrivo della primavera. La

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Fig. 1 – Bruciatura delle paglie di riso in pieno campo nel Vercellese.

Fig. 2 – Risaie allagate in inverno a Zeme (Pavia).

propensione di tali agricoltori alla sperimentazione portò pertanto alla messa a punto della cosiddetta tecnica della sommersione invernale che ben si accorda alle preoccupazioni di alcune "anime belle" per la scarsità di acqua nella stagione invernale prima degli obblighi della portata invernale minima.

I molti vantaggi, agronomici e ambientali, della sommersione invernale

La sommersione invernale è una tecnica agronomica che consiste nel ricoprire la risaia di uno spesso strato d'acqua nel periodo dalla fine della raccolta del riso (settembre-ottobre) fino al termine dell'inverno. Il contatto prolungato delle paglie con l'acqua è in grado di influire in modo significativo sulla stabilità di questo residuo, favorendone il processo di alterazione e degradazione; l'acqua infatti, ammorbidendo le paglie, facendo mantenere al terreno temperature più alte e con il suo stesso movimento, accelera la degradazione dei residui. La tecnica della sommersione, rivelatasi un'ottima alternativa alla bruciatura, con il passare degli anni è stata affinata e, in alcune aree risicole, è divenuta consuetudine allagare le risaie immediatamente dopo la raccolta ed entrare in campo con attrezzi dotati di ruote di ferro a gabbia che sfibrano grossolanamente le paglie, oltre a interrarle parzialmente per avviarne il processo di degradazione.
Oggi questo sistema di gestione è ormai ampiamente diffuso in alcune aree a forte vocazione risicola: in California ben il 40% della superficie coltivata è allagato durante i mesi invernali; in Spagna, è sommerso in inverno il 62% delle terre a riso del delta dell'Ebro e il 62% di quelle della Valencia; nel parco francese della Camargue, il 7-12% dei 18.000 ettari a riso è attualmente convertito a zona umida anche durante i mesi invernali (Tab.1, Pernollet *et al.* 2015). La maggiore o minore diffusione della pratica della sommersione dipende ovviamente anche dalle politiche agricole nazionali. In alcuni paesi europei i Piani di Sviluppo Regionali all'interno della Politica Agricola Comunitaria riservano incentivi agli agricoltori che la scelgono la pratica della sommersione invernale. Tali incentivi saranno previsti anche nei prossimi PSR in Italia, dove la sommersione invernale è molto poco praticata. Nella Pianura Padana, il ruolo delle risaie nella salvaguardia delle risorse idriche è stato documentato da B. Bolognino (2009).
I positivi effetti agronomici-economici, come anche ambientali, derivanti dalla pratica della sommersione sono documentati da numerosi studi condotti tra gli Stati Uniti e l'Europa. Tali studi sottolineano come i vantaggi ambientali non si limitino soltanto al miglioramento della qualità dell'aria e superino i "costi" determinati dal dispendio d'acqua. L'allagamento delle risaie nella stagione fredda ha, infatti, offerto nuove zone umide artificiali e quindi nuovi luoghi di "ospitalità" e "ristoro" per uccelli acquatici migratori, soprattutto anatre, che attorno alla metà di gennaio si trovano in Europa nel loro viaggio verso sud. La creazione di zone umide artificiali diventa particolarmente importante laddove c'è mancanza di zone umide naturale; si pensi, per esempio, che l'80-90% di delle aree umide naturali dell'area Mediterranea è ormai scomparso (Finlayson *et al.*, 1992), con gravi ripercussioni per ciò che riguarda il mantenimento delle biodiversità.
Osservazioni notturne condotte in Camargue nel corso di una ricerca francese (Pernollet *et al.*, 2015) hanno registrato la media di 34 anatre per ettaro nei campi di riso a sommersione invernale a fronte di 0.14 anatre per ettaro nei campi asciutti. A fermarsi nei campi di riso allagati in inverno sono diverse specie della famiglia delle anatidi tra cui il germano reale, il fischione, il codone comune, l'alzavola, la canapiglia, il mestolone. La presen-

La sommersione invernale delle risaie può mettere d'accordo risicoltori, ardeidi, ambientalisti e birdwatcher!

Tab. 1 – Diffusione della sommersione invernale

Zona	Superficie a riso (ha)	Superficie sommersa
California (USA)	180.000	40%
Mississippi (USA)	>800.000	15%
Ebro delta (Spagna)	21.000	90%
Valencia (Spagna)	15.000	60%
Pianura Padana (Italia)	230.000	0.01%
Camargue (Francia)	18.000	7-8%

za dell'acqua nella risaia anche inverno favorisce l'immagazzinamento del cibo nel suolo e lo rende disponibile per gli uccelli (Fasola e Ruiz, 1996; Sánchez-Guzmán *et al.*, 2007; Rendón *et al.*, 2008; Longoni *et al.*, 2010).
La creazione di questi nuovi "rifugi" per uccelli diventa anche un nuovo sbocco lavorativo per gli imprenditori agricoli. La fauna presente durante l'inverno attira, infatti, gli amanti del birdwatching e i cacciatori che, per poterne godere, stipulano con gli agricoltori dei veri e propri contratti.

La realtà italiana

In Italia, paese tra i maggiori produttori di riso in Europa (53% dell'intera superficie risicola europea), la sommersione invernale è una pratica scarsamente diffusa (meno dell'1%) anche se, essendo i campi di riso allagati sfruttando la gravità, potrebbe essere facilmente praticabile senza costi aggiuntivi in termini di petrolio ed elettricità.
Esistono tuttavia alcuni esempi felici di pratica della sommersione anche nelle risaie italiane. In Lombardia, nel comune di Zeme (Pavia), durante l'inverno le risaie si presentano allagate ormai da una decina d'anni. A mettere in atto questa tecnica è l'Azienda Agricola Braggio, che sta portando avanti un'idea del Prof. Francesco Corbetta, già docente di botanica e appassionato ambientalista. Con la speranza di vedere nuovamente gli aironi nelle risaie circostanti la cascina di famiglia, il rinomato botanico ha intuito che la presenza dell'acqua in risaia, anche durante la fase di riposo del terreno, avrebbe potuto indurre gli uccelli a stazionarvi perfino durante i mesi invernali. Quello che era nato come un esperimento con fini essenzialmente ambientali e zoofili si è rivelato al contempo una pratica agronomica dai positivi effetti e così, da dieci anni, l'Azienda Braggio, che conduce i terreni del Prof. Corbetta, allaga regolarmente una quarantina di ettari da fine ottobre fino all'inizio della primavera (fig. 2).
Sperimentando la sommersione invernale, la famiglia Braggio ha progressivamente affinato la propria tecnica di coltivazione e sfruttato al meglio i vantaggi che questa pratica offre.
Terminate le operazioni di trebbiatura, prima di procedere all'allagamento delle camere, sono rimodellati i solchi realizzati nell'ambito delle misure per la biodiversità finanziate dal PSR della Lombardia, e viene controllata la tenuta degli argini. In seguito, per favorire l'incorporazione della paglia nel terreno, in modo che resti sotto il pelo dell'ac-

Fig. 3 – Erpice a dischi con rulli utilizzato prima della sommersione delle risaie.

Fig. 4 – Un maschio di Germano reale (*Anas platyrhynchos*) dal caratteristico piumaggio (Foto Guerrino Gori).

Fig. 5 – Una Garzetta (*Egretta garzetta*), un ardeide molto legato all'acqua (Foto Guerrino Gori).

qua, è effettuato un passaggio con erpice a dischi combinato ai rulli (fig. 3). Qualora si disponesse di una mietitrebbia con testata falciante in grado di operare ad un'altezza ridotta, la lavorazione delle paglie sarebbe presumibilmente evitabile.
Tra fine ottobre e inizio novembre l'acqua è reimmessa nelle risaie e tolta intorno a metà marzo, in modo che il terreno sgrondi, permettendo il ripristino delle condizioni idonee per la semina. Disponendo di terreni in vicinanza dei distaccamenti dal principale canale adacquatore, l'Azienda Braggio attua la sommersione sugli appezzamenti più prossimi alle prese, in tal modo è possibile disporre dell'acqua iemale addotta dal consorzio irriguo

Fig. 6 – Un Airone cenerino (*Ardea cinerea*) nell'atto d'ingoiare un pesce (Foto Eleonora Gnoffo).

Fig. 7 – Un raro abitante delle risaie: la Spatola (*Platalea leucorodia*) (Foto Eleonora Gnoffo).

Est Sesia, che nel periodo invernale garantisce una portata pari a 110 l sec^{-1}.
Il mantenimento di uno strato d'acqua durante i mesi freddi ha portato, negli anni, a una serie di benefici che dovrebbero indurre gli agricoltori, laddove è possibile, ad adottare questa pratica. Anzitutto, la condizione di sommersione non ha effetti negativi sulla potenziale produttività del terreno, infatti, dal 2005 a oggi l'Azienda Braggio non ha riscontrato cali produttivi.
Grazie all'effetto dell'acqua che determina la naturale decomposizione delle paglie, non è più necessaria l'aratura per interrarle. Inoltre, adottando tecniche di minima lavorazione sia per la sfibratura dei residui colturali in autunno, sia per la preparazione del letto di semina in primavera, il ricorso ad aratura e livellamento col laser è diventato superfluo, traducendosi in una forte riduzione dei costi.
La costante presenza dell'acqua favorisce l'instaurarsi di condizioni termiche in grado di influire sulla biologia dei semi di riso rimasti in campo inducendone la germinazione in autunno e la successiva

Fig. 8 – Un bel primo piano di Nitticora (*Nycticorax nycticorax*), il "corvo della notte" per i suoi canti notturni (Foto Archivio Associazione Ardea di Robbio, Pavia).

morte con i primi freddi, ma anche in primavera sul crodo, quando si vengono a creare le condizioni per la falsa semina. Di fatto, nel lungo periodo, è stata osservata una riduzione della banca semi di riso crodo (Fogliatto *et al.* 2010).
Oltre ai vantaggi agronomici, la sommersione ha dato gli effetti sperati in termini di biodiversità, poiché ogni anno sono in aumento non solo gli aironi, le anatre e le cicogne ma anche le libellule, che possono completare il loro complesso ciclo, e le rane. A buon diritto si può pertanto sostenere che l'esperimento di sommersione invernale di Zeme sia un contributo alla salvaguardia delle biodiversità e un positivo esempio di pratica agricola risicola.

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THESE CANARD-RIZICULTURE
(Janv 2013-Janv 2016)

L'inondation hivernale des rizières en Europe

Les canards d'Europe aiment les rizières inondées en Hiver

NOMBRE DE CANARDS = ZONE HUMIDE + RIZIERES INONDEES

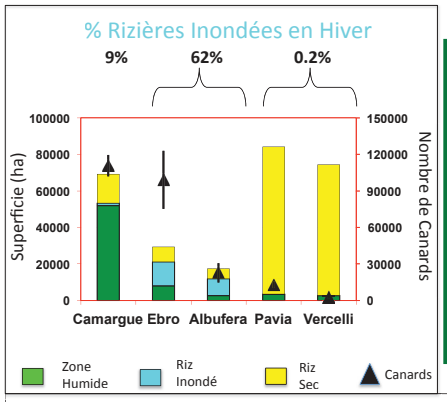
Comparaison Paysages: 5 zones rizicoles européennes en hiver

QUESTION : Laquelle de ces variables Superficie en:

- Rizières sèches en hiver
- Rizières inondées en hiver
- Zones humides naturelles
- Combinaison de ces variables

explique le mieux le nombre de canards hivernants présents sur les paysages rizicoles européens?

L'inondation hivernale en Europe & Les Canards Hivernants

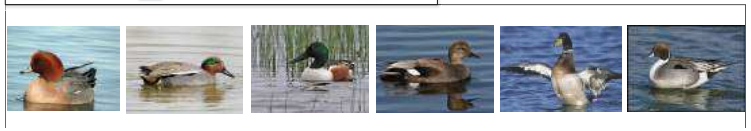


REPONSE :

L'abondance des canards hivernants est positivement liée à la présence de zones humides au sens large,

c'est-à-dire à la somme des zones humides naturelles et des rizières inondées.

CANARDS= ZONE HUMIDE + RIZIERES INONDEES



Des paysages contrastés

Proportion de zones humides par rapport aux rizières varie grandement avec par ordre décroissant de conservation : Camargue (75%) > Ebre (40%) > Albufera (18%) > Pavie (4%) > Vercelli (1%).

Toutes les rizières ne se valent pas en hiver

Proportion inondée varie considérablement :
Espagne : 62% (MAE)
Camargue : 9% (chasse)
Italie : 0.2% (chasse)

CONCLUSION

L'inondation hivernale présente un fort intérêt pour les canards et serait intéressante à mettre en place tout le long de la voie de migration, en commençant par les régions où la plupart des zones humides naturelles ont été détruites comme c'est le cas dans la plaine de Pô en Italie. Pour la Camargue, une analyse coûts/bénéfices est en cours afin de voir si cette pratique serait applicable et économiquement acceptable.

EN SAVOIR PLUS SUR LE PROJET

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TESIS PATOS-ARROZALES
(Enero 2013-Enero 2016)

La inundación invernal de los arrozales en Europa

A los patos europeos les gustan los arrozales inundados en invierno

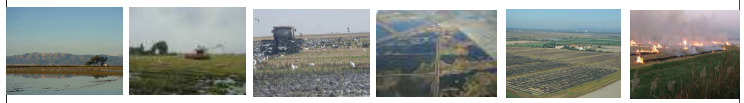
NUMERO DE PATOS = HUMEDALES NATURALES + ARROZALES INUNDADOS

Comparación Paisajes: 5 zonas arroceras europeas en invierno

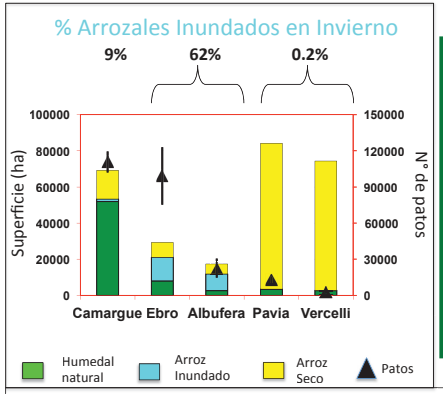
PREGUNTA
? Cuales de estas variables explican mejor el numero de patos invernantes presentes en los paisajes arroceros europeos ?

La superficie de:

- Arrozales secos en invierno
- Arrozales inundados en invierno
- Humedales naturales
- Combinación de estas variables



Inundación Invernal en Europa - Patos Invernantes

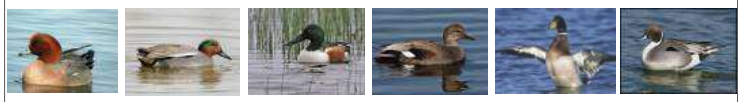


RESPUESTA :

La abundancia de patos invernantes es positivamente ligada a la presencia de humedales en el sentido amplio de la palabra.

Es decir a la suma de las superficies de los humedales naturales y de los arrozales inundados.

PATOS= HUMEDALES NATURALES+ ARROZALES INUNDADOS



En los paisajes contrastados

La proporción de humedales naturales con respecto a los arrozales varia mucho. Por orden decreciente de conservación : Camargua (75%) > Ebro (40%) > Albufera (18%) > Pavia (4%) > Vercelli (1%).

Los arrozales se diferencian durante el invierno entre países

Según los intereses, la proporción inundada varia considerablemente :
España : 62% (Medida Agro-Ambiental)
Francia : 9% (caza de patos)
Italia : 0.2% (caza de patos)

CONCLUSION

La inundación invernal es de gran interés para los patos invernantes. Por ello seria interesante conservar la MAA en España y promover la inundación a lo largo de la vía de migración, empezando por las regiones donde la mayor parte de los humedales naturales desaparecieron, como es el caso en la valle del rio Pô en Italia. En la Camargua se esta llevando a cabo un análisis costo/beneficio para ver si esta practica seria aplicable y económicamente favorable

MAS INFORMACION SOBRE EL PROYECTO ?
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TESI ANATRA-RISICULTURA
(Genn 2013-Genn 2016)

L'allagamento invernale delle risaie in Europa

Le anatre europee amano le risaie allagate in inverno

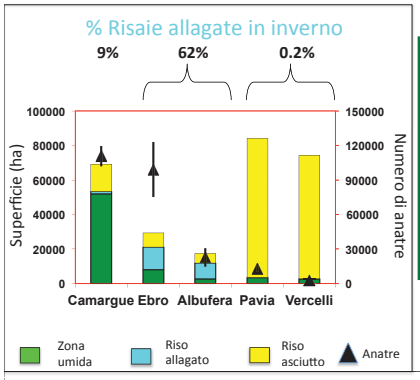
NUMERO DI ANATRE = ZONA UMIDA + RISAIE ALLAGATE

Paesaggi a confronto: 5 zone risicole europee in inverno

QUESITO : Quale tra queste variabili indica meglio il numero di anatre invernali presenti nelle zone risicole europee?
Superficie in:

- Risaie in asciutta in inverno
- Risaie allagate in inverno
- Zone umide naturali
- Combinazione fra queste variabili

L'allagamento invernale in Europa & le anatre invernali

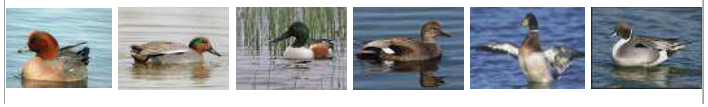


RISPOSTA:

L'abbondanza delle anatre invernali è legata positivamente alla presenza delle zone umide in senso largo.

Ossia alla somma delle zone umide naturali e delle risaie allagate.

ANATRE = ZONE UMIDA+ RISAIA ALLAGATA



Paesaggi in contrasto

Il rapporto fra le zone umide e il numero di risaie varia notevolmente a seconda del paese. In ordine decrescente di conservazione : Camargue (75%) > Ebro (40%) > Albufera (18%) > Pavie (4%) > Vercelli (1%).

Non tutte le risaie sono equivalenti in inverno

La proporzione di allagate varia considerevolmente:
Spagna: 62% (Misure agroambientali)
Camargue : 9% (caccia)
Italia : 0.2% (caccia)

CONCLUSIONE

La sommersione invernale offre un grande vantaggio alle anatre. Sarebbe interessante poter applicare questa tecnica lungo tutto il canale di migrazione, cominciando dalle zone o dalla maggior parte delle zone umide naturali che sono state distrutte, come nel caso della piena del delta del Po' in Italia (allagamento facile sfruttando la gravità). Attualmente è in corso un analisi costi/benefici per il territorio della Camargue. Questo studio mira ad esaminare se questa pratica è applicabile e economicamente accetabile.

PER MAGGIORI INFORMAZIONI SUL PROGETTO
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THESE CANARD-RIZICULTURE
(Janv 2013-Janv 2016)

Impact des canards hivernants sur les chaumes de la paille et sur la banque de graines adventices

Les canards réduisent les chaumes mais pas les graines d'adventices

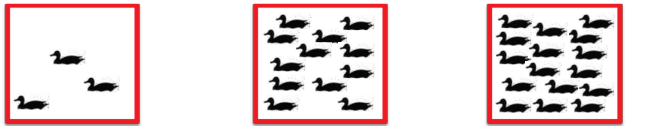
Objectif : Evaluer si l'inondation hivernale des rizières attirant les oiseaux d'eau, peut être bénéfique aux agriculteurs.

Mesure expérimentale de l'impact :

a) **du piétinement des canards sur la quantité de chaumes debout (non immergées)**
b) **des canards sur la quantité et la diversité des graines adventices dans le sol**

Et cela à trois densités (canards/ha) : **D1= 5, D2= 23, D3= 300**

Densitées nocturnes de Camargue | Pratique diurne



Années 80 (5 canards/ha) | Hiver 2013-2014 (23 canards/ha) | Asiatique (300 canards/ha)

25 cm de côté

Chaumes

5 cm de profondeur

Carottes

Analyses statistiques

EN SAVOIR PLUS SUR LE PROJET
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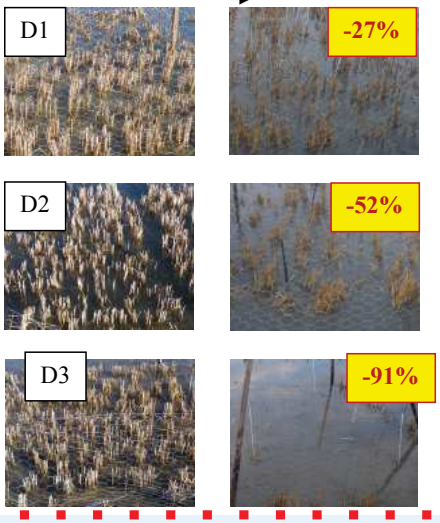
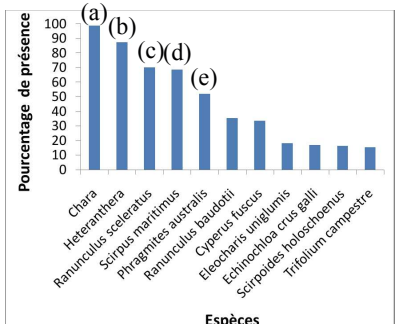
Résultats : Chaumes

Avant → Après



Graines

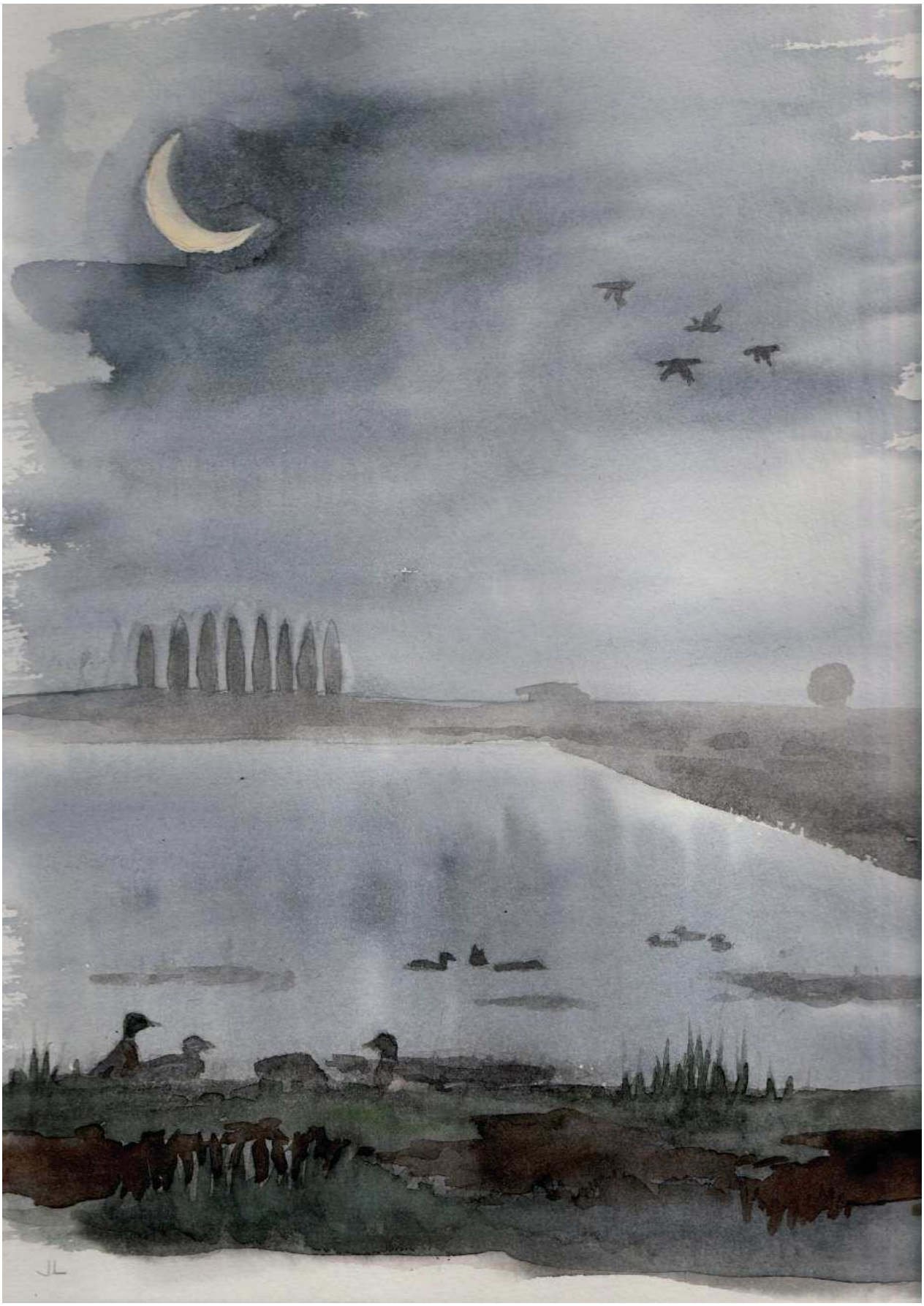
Des adventices majeures des rizières en Camargue :
36 espèces
5 espèces dans + de 50% des carottes
Quantité = 110 kg/ha



Réduction limitée de ces graines par les canards :
Très grande variabilité de la banque de graines au sein d'une même parcelle.

CONCLUSION

L'attraction des canards sur rizières inondées apporterait **peu d'avantages au niveau de la réduction des graines** de mauvaises herbes. En revanche, cette pratique permettrait la **diminution du nombre de chaumes debout**, et donc une **augmentation de la décomposition de la paille**, par l'action conjuguée de l'eau et du piétinement des canards. Les bénéfices peuvent aller **jusqu'à 50% d'immersion des chaumes avec la densité actuelle** de canards sauvages, et **jusqu'à 90% si on utilise une forte densité de canards d'élevage**. L'inondation hivernale permet d'allier conservation de la biodiversité et bénéfices agronomiques, ce qui est particulièrement intéressant.



Water painting by Jacques Lesser

"Heureux soient les fêlés car ils laisseront passer la lumière" Michel Audiard

Sung to the tune / A chanter sur l'air de "My Girl" of Nirvana

My duck, my duck, don't lie to me
Tell me where did you sleep last night
In the pound, in the marsh,
Where the hunters never hunt
I'm going to count…my duck

My duck, my duck, where will you go
I'm going where the cold wind blows
In the pound, in the marsh,
Where the hunters never hunt
I'm going to count…my duck

My duck was a hard working duck
Just about a mile from here
His head was found in a close montille
But his body never was found

My duck, my duck, don't lie to me
Tell me where did you sleep last night
In the pound, in the marsh,
Where the hunters never hunt
I'm going to count…my duck

My duck, my duck, where will you go
I'm going where the cold wind blows
In the pound, in the marsh,
Where the hunters never hunt
I'm going to look for my duck

Chanson écrite par Mailis, David, Elvin, Anne B, Anne L, Radka.

28 GRAND ANGLE

«Duck Dynasty»
l'Amérique dans l'appeau

RÉSUMÉ

Les systèmes cultivés dominent la surface du globe et représentent tant une menace qu'une opportunité pour la conservation de la biodiversité. Certaines pratiques agricoles permettent en effet la production de nourriture tout en assurant une certaine protection de l'environnement. L'inondation hivernale des rizières a été identifiée en Amérique du Nord et en Asie comme une pratique offrant des avantages à la fois pour les oiseaux d'eau et les agriculteurs. Par une série d'études empiriques et d'expérimentations, nous avons testé si des bénéfices similaires pouvaient être espérés en Europe. Les effectifs moyens de canards dans cinq grandes régions rizicoles européennes sont effectivement positivement corrélés aux superficies totales des zones humides (zones naturelles plus rizières inondées), suggérant une complémentarité de ces deux types d'habitats pour la conservation des canards. En appliquant différentes pratiques post-récolte sur 50 rizières en Camargue (France), nous mettons en évidence l'existence de ressources abondantes pour les canards hivernants (près de 500 kg/ha de graines de riz et d'adventices au sol après la récolte). La disponibilité en graines diminue fortement au cours de l'hiver (-89% pour la masse de riz et -69% pour celle d'adventices), cette déplétion étant accentuée par la pratique d'un labour. L'inondation hivernale est le principal facteur explicatif de la fréquentation nocturne des rizières par les canards (24 canards/ha en moyenne dans les parcelles inondées et 0,3 dans les parcelles sèches). En retour, des tests expérimentaux montrent que les canards se nourrissant dans les rizières inondées diminuent le nombre de chaumes de paille, mais n'ont pas d'effet significatif sur la banque de graines d'adventices. Une analyse coûts-bénéfices prenant en compte les contraintes et les avantages agronomiques et environnementaux évalue la faisabilité économique de la mise en eau hivernale des rizières en Camargue. La moisson en rizières inondées est quatre fois plus rentable pour les agriculteurs et plus de huit fois plus pour la société camarguaise que le brûlage-labour traditionnel, qui n'est pas économiquement acceptable (ratio bénéfices/coûts pour les agriculteurs 4,15 vs 1,02, pour la société 6,67 vs 0,78). L'inondation hivernale des rizières en Europe est bénéfique à la fois pour les agriculteurs et pour les canards hivernants. En Camargue, en plus d'être économiquement réaliste pour les agriculteurs, cette pratique est fortement bénéfique pour l'environnement, et mérite d'être encouragée.

Mots clés: Aménagement des habitats, Bénéfices agronomiques, Services écosystémiques, Canards hivernants, Disponibilité en nourriture, Rizières, Conservation, Agroécosystèmes

ABSTRACT

Cultivated systems dominate the Earth and represent both a threat and an opportunity for the conservation of biodiversity. Some agricultural practices can simultaneously allow abundant food production and some protection of the environment. Winter flooding of rice fields has been identified as a habitat management with potential advantages for both wintering ducks and farmers in Asia and North America. Through a set of empirical and experimental studies, we tested if similar benefits could be expected in Europe. The mean number of wintering ducks in five major rice production regions of Western Europe is positively related with the total wetland area (natural wetlands plus flooded rice fields), suggesting complementarities between these habitats for waterfowl conservation. Applying a variety of agricultural practices to 50 harvested rice fields in Camargue (France), we demonstrate the existence of vast amounts of duck food resources (ca. 500 kg/ha of rice and weed seeds remaining on the ground after harvest). Seed availability greatly decreases across the winter (-89% for rice seed mass and -69% for weeds), seed depletion being accentuated by ploughing. Winter flooding is the main determinant of nocturnal use of the fields by wintering ducks (on average 24 and. 0.3 ducks/ha in flooded and unflooded fields, respectively). In return, experiments show that waterfowl foraging in flooded rice fields enhance straw stalks reduction, but do not significantly reduce the weed seed bank. A cost-benefit analysis was eventually carried out to evaluate whether winter flooding in France would be economically realistic considering agronomic and environmental constraints and advantages. Harvesting rice in flooded fields is four times more profitable to farmers and more than eight times more profitable for the Camargue society than the traditional burning-ploughing (benefits-to-costs ratios for farmers: 4.15 vs. 1.02; for society: 6.67 vs. 0.78). Promoting winter flooding of rice fields in Europe would benefit both farmers and wintering ducks. In Camargue, in addition to be economically realistic for farmers, this practice is strongly desirable from an environmental conservation point of view, and should therefore be promoted.

Keywords: Habitat management, Agronomic benefits, Ecosystem Services, Wintering ducks, Food availability, Ricefields, Conservation, Agroecosystems

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