Cropping Miscanthus x giganteus in commercial fields : from agro-environmental diagnostic to ex ante design and assessment of energy oriented cropping systems

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Cultiver *Miscanthus* x *giganteus* en parcelles agricoles :

du diagnostic agro-environnemental à la conception-évaluation *ex ante* de systèmes de culture à vocation énergétique

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Introduction générale

Le modèle énergétique actuel repose massivement sur les ressources fossiles comme le charbon, les hydrocarbures et le gaz naturel. En 2008, environ 80% de l'énergie primaire consommée à l'échelle mondiale était d'origine fossile (IEA, 2010). Ce modèle est appelé à évoluer sous l'effet de plusieurs moteurs. La combustion de ces ressources représente tout d'abord la première source d'émissions de gaz à effet de serre d'origine anthropique : c'est donc un contributeur majeur au changement climatique (IPCC, 2007). La répartition géographique de ces ressources est de plus très inégale, ce qui peut provoquer des tensions géopolitiques (IEA 2010). Enfin, les ressources fossiles sont en voie de raréfaction alors que la consommation d'énergie mondiale connaît une hausse rapide autour de 2-3% par an, notamment sous l'effet de la rapide industrialisation des économies du Sud-Est de l'Asie, du Brésil, de la Chine et de l'Inde. Le secteur des transports est particulièrement concerné : il représente ainsi environ un tiers de la consommation d'énergie européenne pour un cinquième des émissions de gaz à effet de serre (EEA, 2006). Dans ce contexte, l'Union Européenne a adopté en 2008 le paquet Energie-Climat (CEC, 2008) qui instaure l'objectif des « 3*20 » à atteindre d'ici 2020 : (i) réduction des émissions de gaz à effet de serre de 20% par rapport à celles de 1990, (ii) réduction de la consommation d'énergie de 20% par rapport aux prévisions réalisées en poursuivant le modèle actuel et (iii) augmentation de la part de l'énergie produite de manière renouvelable d'environ 9% à 20%. Dans le secteur des transports, il est prévu qu'au moins 10% de l'énergie destinée au secteur des transports soit produite de manière renouvelable, sous réserve du respect de critères de durabilité**.**

Dans l'état actuel des connaissances et des techniques, deux types d'énergie sont concernées dans le secteur des transports : l'électricité et les carburants ; ces derniers sont désignés par le terme biocarburants lorsqu'il s'agit de carburants renouvelables. Si le développement de véhicules électriques a sensiblement progressé ces dernières années, la légèreté et le caractère compact des carburants liquides leur confèrent encore une capacité de stockage d'énergie 50 fois supérieure à celles des meilleures batteries (Bessou *et al.*, 2011). A l'avenir, les piles à combustibles fonctionnant à l'hydrogène pourraient remplacer les batteries actuelles. Ce n'est toutefois qu'une perspective à long terme nécessitant des travaux de recherche-développement importants. De plus, l'électricité, comme l'hydrogène, sont des vecteurs énergétiques secondaires qui doivent être produits à partir de sources d'énergie primaires, ce qui peut être associé à des fortes émissions de gaz à effet de serre (Bessou *et al.*, 2011). Le développement des biocarburants constitue donc un enjeu majeur. Les biocarburants font partie des énergies renouvelables produites à partir de la biomasse en convertissant l'énergie chimique contenue dans les molécules des organismes vivants en sources d'énergie directes à travers des procédés biologiques, mécaniques ou thermochimiques. Au-delà des biocarburants dits de première génération (1G) déjà commercialisés, des recherches sont menées afin de mettre au point de nouvelles formes de biocarburants plus compétitives et plus durables. Si les biocarburants constituent bien une forme d'énergie renouvelable (sous réserve que les écosystèmes permettant la production de biomasse ne soit pas surexploités ou dégradés), cela n'est toutefois pas suffisant pour garantir leur durabilité, comme le souligne Bessou *et al.* (2011) : il faut de plus que l'utilisation de cette ressource ne soit pas associée à une dégradation de l'environnement, qu'elle soit favorable d'un point de vue social et viable économiquement.

Le projet Futurol, qui finance ce travail de thèse, est un projet de recherche-développement français initié en 2008 qui vise à mettre sur le marché un procédé durable et compétitif de production d'éthanol de deuxième génération par voie biochimique à l'horizon 2015. Ce projet, porté par la SAS[1] PROCETHOL 2G, regroupe à la fois des partenaires industriels (ex : Total, groupe Lesaffre), des partenaires agricoles (ex : coopératives Champagne Céréales et Tereos, Confédération Générale des planteurs de Betteraves), des partenaires financiers (Crédit Agricole ou UNIGRAINS), ainsi que des partenaires de R&D (ARD[2], IFPEN[3], INRA). Le projet Futurol comporte la construction d'un pilote, puis d'un prototype de production d'éthanol. L'installation pilote a été inaugurée en 2011 sur le site agro-industriel de Pomacle-Bazancourt dans la Marne. Il comporte deux grands axes de recherche : l'un consacré aux procédés de transformation de la biomasse et un module consacré aux ressources candidates à cette transformation, le module « Ressources ligno-cellulosiques ». La finalité de ce module, dans laquelle s'inscrit ce travail de thèse, est de fournir les connaissances et les démarches/méthodes nécessaires à la mise en place, dans un contexte de développement durable, de cultures ligno-cellulosiques adaptées aux conditions locales dans une logique de constitution de bassin d'approvisionnement pour de futures unités de production de bioéthanol de deuxième génération.

[1] Société par Actions Simplifiées

[2] Agro-Ressources et Développement

[3] Institut Français du Pétrole et des Energies Nouvelles

L'objectif de ce travail de thèse est de contribuer à l'étude de la durabilité de la production de biocarburants de deuxième génération à partir d'une des ressources candidates, la culture de *Miscanthus* x *giganteus*, en s'appuyant sur un diagnostic agro-environnemental combiné à une évaluation multicritère de systèmes de culture. Le premier chapitre, après avoir présenté les intérêts et les limites associés à la production de biocarburants, expose l'état des connaissances sur le comportement au champ de *Miscanthus* x *giganteus* afin de présenter les questions de recherche qui font l'objet de ce mémoire. Les deuxième et troisième chapitres sont consacrés au diagnostic agro-environnemental de la culture de *Miscanthus* x *giganteus*. Le quatrième chapitre étudie l'évolution à long-terme des rendements de la culture. Le cinquième chapitre compare des systèmes de culture comprenant *Miscanthus* x *giganteus* à des systèmes de culture comprenant d'autres ressources candidates à la production de biocarburants de deuxième génération. Enfin, les résultats obtenus dans les chapitres trois à cinq sont discutés dans le sixième.

Chapitre 1.

Contexte et problématique

1. Contexte et enjeux autour de la production de biocarburants

1.1. De la première à la deuxième génération de biocarburants

La production de biocarburants suscite à la fois beaucoup d'espoirs et de controverses. Les biocarburants représentent une opportunité pour (i) lutter contre le réchauffement climatique tout en produisant de l'énergie d'origine renouvelable et (ii) renforcer l'indépendance énergétique des pays peu pourvus en ressources fossiles, (iii) tout en constituant un nouveau débouché pour les filières agricoles végétales (FAO, 2008, 2011). Ils font toutefois également l'objet de nombreuses critiques, en particulier lorsqu'il s'agit des biocarburants de première génération (1G).

1.1.1 Des controverses entourant les biocarburants de première génération…

Les biocarburants 1G correspondent aux carburants produits à partir des organes de réserve de certaines plantes cultivées : graines, tubercules ou tiges saccharifères. Ce sont les biocarburants produits actuellement à travers deux grandes filières industrielles de production (**Figure 1. 1**). La première filière concerne les huiles végétales qui sont utilisées après estérification pour les véhicules diesel. On obtient un produit nommé EMHV (ester méthylique d'huile végétale) ou biodiesel[4]. La production s'appuie actuellement sur les huiles de colza ou de tournesol en France et en Europe, mais également de soja (Etats-Unis) ou de palme (Brésil, Asie du Sud-Est). En 2007, la production mondiale de biodiesel atteignait 6,2 milliards de litres, dont 60% étaient produits en Europe (FAO, 2008). La filière éthanol comprend l'éthanol et l'ETBE (éthyl-tertio-butyl-ether)[5] et concerne les véhicules essence. L'éthanol est principalement produit à partir de betterave ou de céréales à paille (blé, orge, seigle) en Europe, de maïs aux Etats-Unis et de canne à sucre au Brésil. A l'heure actuelle, les Etats-Unis et le Brésil dominent le secteur de la production mondiale d'éthanol qui atteignait 52 milliards de litres en 2007 (FAO, 2008). En 2006, environ la moitié de cet éthanol était produit aux Etats-Unis à partir de 14% de la production nationale de maïs (Möller *et al.*, 2007 in Bessou *et al.,* 2011). Le Brésil, avec comme substrat la canne à sucre, représente deux cinquièmes de la production mondiale et produit ainsi environ 21% de son carburant destiné au transport (OECD, 2006). La production totale de biocarburants en France représentait en 2011 environ 5% du carburant destiné au transport (dont 4% sous forme de biodiesel) (Lorne, 2011). En 2007, 1 100 000 hectares étaient mobilisés en France pour la production de biocarburants de première génération, dont un tiers de jachères industrielles.

[4] Produit composé à 90 % d'huiles végétales pures et 10 % de méthanol
[5] L'ETBE est obtenu en recombinant un hydrocarbure pétrolier, l'isobuthène, et l'éthanol dans la proportion respective de 53 % et 47 %.

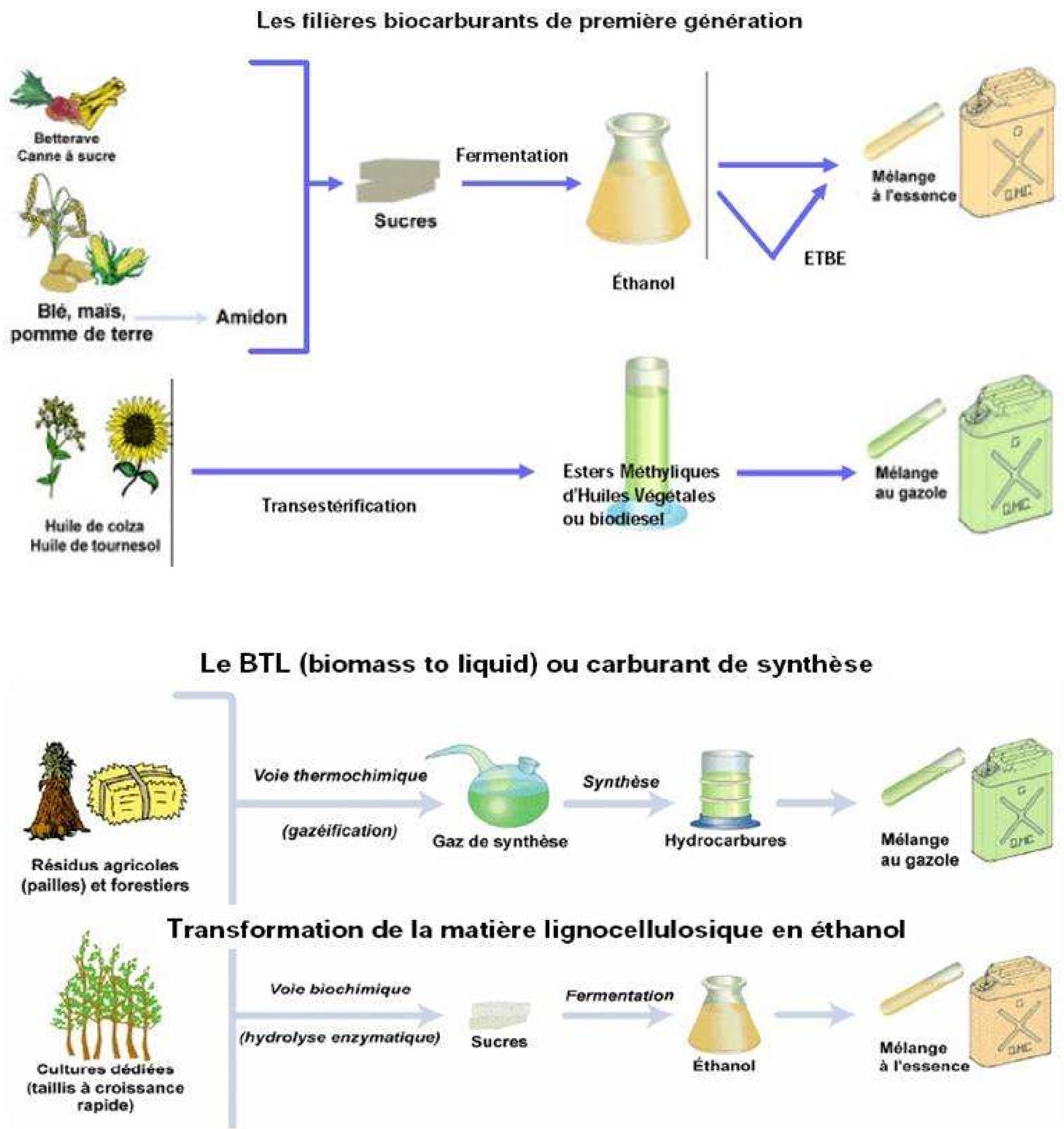

Figure 1. 1 : Ressources et voies de production des biocarburants de première et deuxième génération.

Ces surfaces ont été multipliées par trois depuis 1998, en raison notamment d'un contexte politique très incitatif : autorisation de cultures non alimentaires sur les jachères, subvention aux cultures énergétiques instaurée en 2004 (supprimée depuis), dispositions fiscales incitatives, objectifs d'incorporation ambitieux. En 2006, 88% de ces surfaces étaient occupées par du colza et la moitié de la production française de cette culture était dédiée à la production de biodiesel (Guindé *et al.*, 2008). A l'inverse, seuls 8% des surfaces de tournesol, 6% de celles de betterave et moins de 1% de celles de blé étaient concernés par cette production (Guindé *et al.*, 2008).

La production et l'utilisation de biocarburants permettent d'éviter les émissions de gaz à effet de serre induites par la combustion de leurs équivalents fossiles. Toutefois, la production de la ressource, puis sa transformation en biocarburants, provoquent également des émissions de gaz à effet de serre (**Figure 1.2**) : il convient donc de faire un bilan des émissions de gaz à effet de serre sur l'ensemble du cycle de vie du carburant, du berceau à la tombe, selon le principe de l'analyse de cycle de vie (ACV) (**Figure 1. 2**) Si plusieurs ACV concluent que l'utilisation de ces biocarburants permet de réduire les émissions de gaz à effet de serre comparée à leurs équivalents fossiles, l'amplitude de réduction est extrêmement variable selon les travaux (Quirin *et al.*, 2004; von Blottnitz and Curran, 2007). Farrell *et al.* (2006) montrent même que l'utilisation de biocarburants 1G produits à partir de maïs peut sous certaines hypothèses être à l'origine d'émissions de gaz à effet de serre supérieures à celles de son équivalent fossile. Une grande part des incertitudes entourant ces bilans de gaz à effet de serre viennent de l'estimation des émissions de gaz à effet de serre associées à la production agricole, alors que celles-ci représentent par exemple de 34 à 44% des émissions associés à l'éthanol de maïs aux Etats-Unis (Farrell *et al.*, 2006) et plus de 80% des émissions dans le cas des huiles végétales pures (ADEME/DIREN, 2002). Ces incertitudes résultent principalement de la prise en compte des émissions de protoxyde d'azote (N_2O) par les sols agricoles (Crutzen *et al.*, 2007; Bowman *et al.*, 2010) et de la prise en compte des émissions de dioxyde de carbone (CO_2) liées au possible déstockage de carbone provoqué par les changements d'usage des sols (Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Melillo *et al.*, 2009). Le protoxyde d'azote est naturellement produit dans les sols au cours des processus microbiens de dénitrification et nitrification. Sa production est largement influencée par la disponibilité en azote minéral : par conséquent, l'utilisation accrue d'engrais azotés tend à augmenter les émissions de N_2O par les sols (IPCC, 2006). Ces émissions représentent 46% des émissions de gaz à effet de serre d'origine agricole (Baumert *et al.*, 2005). La quantité de carbone organique contenue dans un sol dépend fortement du type de végétation : les sols cultivés contiennent 1,6 fois moins de carbone organique que les sols de forêts ou de prairies permanentes (Antoni and Arrouays, 2007). Le déstockage de carbone peut être direct ou indirect. Il est direct lorsque la culture destinée à la production de biocarburants est cultivée à la place d'un couvert végétal permettant un stockage important de carbone dans le sol.

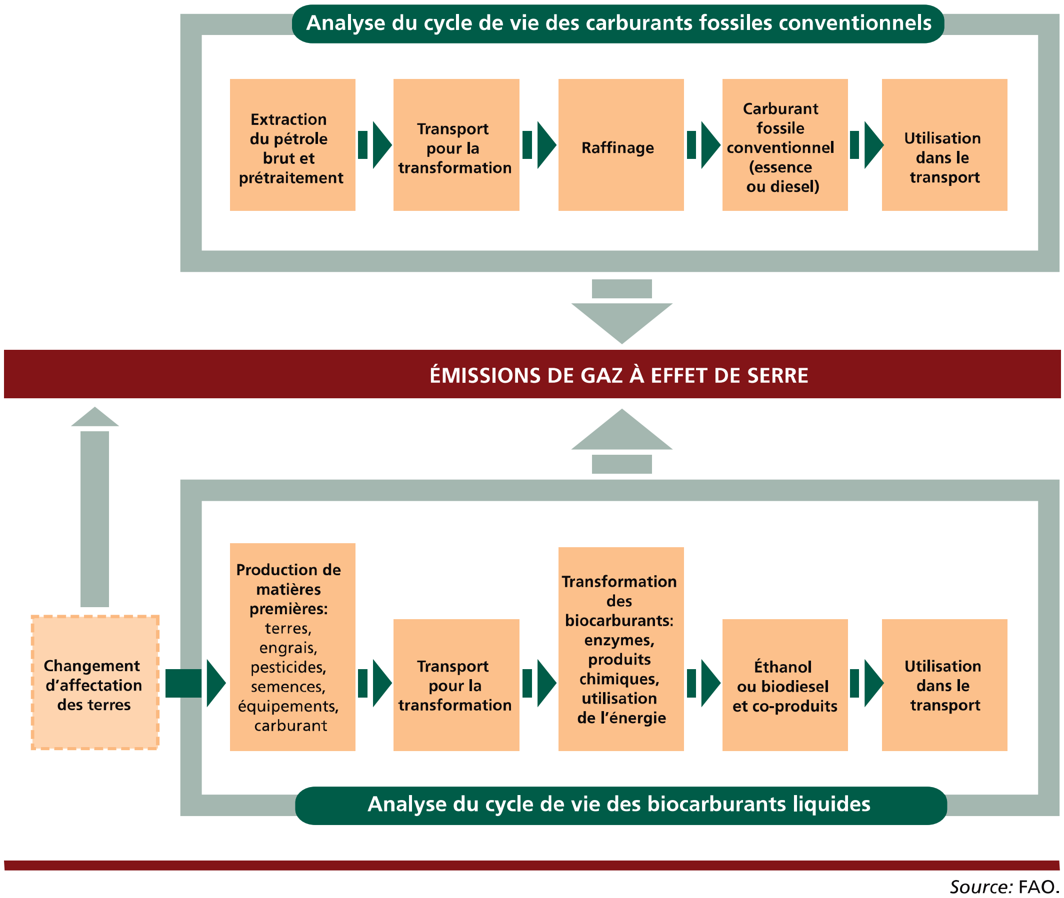

Figure 1. 2 : Emissions de gaz à effet de serre au cours du cycle de vie de carburants fossiles conventionnels (en haut) et de biocarburants liquides (en bas).

Lorsque les changements d'usage des sols dépassent les parcelles concernées par la production de biocarburants et induisent un déstockage de carbone, il s'agit alors de déstockage indirect.

Au-delà des émissions de gaz à effet de serre, ce sont également les bilans énergétiques associés à la production de biocarburants 1G qui sont variables (ECOBILAN, 2006). Ces bilans sont calculés comme la différence entre la quantité d'énergie procurée par la combustion des biocarburants et la quantité d'énergie consommée pour produire la ressource puis la transformer. Ainsi, Hill (2007) indique que, selon les études considérées, l'énergie libérée par la combustion d'éthanol produit à partir de maïs grain varie de 20 à 28 MJ l^{-1} tandis que l'énergie nécessaire à la production d'un litre de ce même éthanol varie de 17 à 27 MJ l^{-1}. D'autre part, les effets de la production de biocarburants 1G sur la biodiversité et la ressource en eau sont également dénoncés. Enfin, les effets induits (réduction des terres disponibles, augmentation des prix des produits agricoles) sur la production alimentaire font également l'objet de vives discussions. Les hausses spectaculaires des prix alimentaires en 2007 ont ainsi été attribuées en partie à la production de biocarburants (FAO, 2008).

Pour limiter un certain nombre des impacts négatifs des biocarburants évoqués ci-dessus, l'Union Européenne a mis en place un système de certification reposant sur quatre critères de durabilité (Directive 2009/28/EC, 2009). Le premier fixe **un niveau minimum d'émissions de gaz à effet de serre évitées par la production de biocarburants (35% dès l'application de la directive puis 50 voire 60% d'ici 2017)**. Les deuxième et troisième critères portent sur les changements d'usage des sols qui doivent être évités. En particulier, la production de biocarburants est tenue d'éviter (i) une perte trop importante de biodiversité, ainsi (ii) qu'un déstockage massif de carbone. Enfin, cette production doit respecter les bonnes pratiques agricoles et environnementales dans le but d'entrainer de faibles impacts environnementaux à l'échelle locale.

1.1.1 … aux espoirs suscités par les biocarburants de deuxième génération.

Les biocarburants 2G[6] sont produits à partir de lignocellulose, principal constituant des parois des cellules végétales. Ces parois représentent 60 à 80% des tiges des espèces arborées, 30 à 60% des tiges des espèces herbacées et 15 à 30% des feuilles (Möller *et al.,* 2007, in Bessou *et al.,* 2011). Les procédés de transformation nécessaires à cette deuxième génération sont encore à l'étude et se divisent en deux grandes familles : la voie thermochimique[7], qui aboutit à la production d'hydrocarbures et la voie biochimique, qui permet la production d'éthanol (**Figure 1.1**). Nous nous concentrons ici sur la voie biochimique qui est celle étudiée dans le cadre du projet Futurol. Les méthodes de transformation sont connues mais les travaux actuels visent essentiellement à les rendre économiquement et énergétiquement viables (Bessou *et al.*, 2011; Borrion *et al.*, 2012). La lignocellulose est en effet un substrat complexe qui présente une forte récalcitrance à la dégradation (Möller *et al.,* 2006, in Bessou *et al.,* 2011) : il est nécessaire de délignifier le substrat pour libérer la cellulose et l'hémicellulose, avant de dépolymériser ces sucres complexes pour obtenir des sucres simples dont la fermentation produit de l'éthanol. A notre connaissance et d'après Borrion *et al.* (2012), il n'y a pas à l'heure actuelle d'usine de production de bioéthanol à partir de lignocellulose, bien que des pilotes, *i.e.* des unités de production test à petite échelle, aient été construits en Europe et aux Etats-Unis.

Les gisements de biomasse lignocellulosique exploitables sont de quatre types (Cormeau and Gosse, 2007) :

- **Les résidus lignocellulosiques**. Ils peuvent être d'origine agricole (ex : paille de céréales, rafles de maïs, tige de colza), sylvicole, industrielle (ex : liqueurs noires de l'industrie papetière) ou urbaine (palettes, cagettes, résidus de bois sur les chantiers) ;
- **Les coproduits des biocarburants 1G;**
- **Les ressources forestières ;**
- **Les cultures lignocellulosiques**. Il s'agit de ressources agricoles qui peuvent être :
    - des plantes annuelles : céréales à paille (blé, triticale, orge), maïs, sorgho ;
    - des plantes pluriannuelles cultivées entre deux et cinq ans : fétuque élevée, luzerne ;
    - des plantes pérennes herbacées (miscanthus, switchgrass, canne de provence) ou arbustives (peuplier, saule, eucalyptus, légumineuses comme le robinier ou l'aulne) cultivées en Taillis à Courte Rotation (TCR) ou en Taillis à très Courte Rotation (TtCR) pendant dix à vingt-cinq ans

La diversité des ressources lignocellulosiques exploitables constitue le grand atout des biocarburants 2G comparés aux biocarburants 1G ; nous y reviendrons par la suite à partir de

[6] Des recherches sont également menées dans le but de produire des biocarburants à partir des lipides des micro-algues ou encore en utilisant des bactéries ou des levures, biocarburants que certains nomment déjà de troisième génération voire de quatrième génération.

[7] La gazéification de la biomasse ouvre également la voie à la production d'hydrogène et à la co-génération (production d'électricité et de chaleur).

l'exemple des ressources agricoles. Bien que le procédé de transformation n'ait pas encore dépassé le stade expérimental, de nombreuses études ont déjà été menées pour étudier la durabilité de ce type de biocarburant. Un bilan de 53 ACV menées entre 2005 et 2011 sur l'éthanol lignocellulosique souligne ainsi que toutes les études sauf deux concluent à une réduction des émissions de gaz à effet de serre comparées à l'utilisation de carburants fossiles (Borrion *et al.*, 2012). Toutefois, l'ampleur de la réduction est à nouveau extrêmement variable entre études. Dans ces mêmes études, des résultats contrastés sont obtenus au sujet des impacts environnementaux, notamment ceux concernant la ressource en eau. Whitaker *et al.* (2010) ainsi que Borrion *et al.* (2012) montrent que la variabilité des résultats entre études vient de différences méthodologiques (concernant en particulier les limites du système étudié et les méthodes d'allocation utilisées) mais aussi de l'incertitude entourant les données utilisées, qu'il s'agisse des données concernant la phase de transformation de la ressource ou des données décrivant la production de la ressource. Whitaker *et al.* (2010) soulignent **le poids des données décrivant la fertilisation et les rendements sur les bilans de gaz à effet de serre et les bilans énergétiques**. Batidzirai *et al.* (2012) montrent également que **l'estimation des rendements**, conjointement à l'estimation des terres disponibles, est un élément central pour estimer les potentiels de production de bioénergie à l'échelle d'un pays et par suite, à l'échelle européenne ou mondiale.

1.2. Diversité des ressources agricoles candidates à la production de biocarburants 2G et stratégies de production

Comparés aux biocarburants de première génération, les procédés de production de biocarburants de deuxième génération présentent l'immense avantage de concerner une grande diversité de ressources. Cette diversité permet d'envisager des stratégies variées et potentiellement complémentaires de production. La présence de ressources non agricoles (ressources forestières) et de déchets (sylvicoles, industriels, urbains) parmi les ressources candidates permet de limiter la concurrence avec les productions alimentaires et les autres productions non alimentaires. Ces ressources ne font toutefois pas l'objet de ce travail et ne seront plus abordées par la suite.

Table 1. 1 : Diversité des ressources agricoles candidates à la production de biocarburants de deuxième génération.

	Plante entière	**Résidus***
Ressource dédiée	Miscanthus Switchgrass TCR et TtCR	
Ressource mixte	Céréales (immatures) Maïs, sorgho (en ensilage) Luzerne Fétuque	Paille de céréales (y compris rafles de maïs) Tiges de luzerne Tiges de colza Cannes de tournesol

*Tous les résidus ont été classés dans les ressources mixtes. Tous ne constituent pas une source de fourrage, mais ils jouent des fonctions importantes vis-à-vis des sols.

Table 1. 2 : Surfaces occupées par des cultures dédiées en France en 2009 (estimées à partir des surfaces ayant souscrit un contrat Jachère Industriel ou Aide aux Cultures énergétiques).

	Surfaces (ha)
Miscanthus	1596
Switchgrass	148
TCR Eucalyptus	136
TCR Peuplier	354
TCR Robinier faux acacia	337
TCR Saule	221

1.2.1 Présentation des grandes catégories de ressources agricoles candidates à la production de biocarburants 2G

Les ressources agricoles candidates peuvent être caractérisées en distinguant (i) les ressources utilisées en plante entière de celles dont on utilise les résidus, et (ii) les ressources dédiées uniquement à la production non alimentaire de celles qui peuvent contribuer à des débouchés alimentaires et non alimentaires (appelée ici ressources mixtes) (**Tableau 1. 1**).

Parmi les plantes entières dédiées, la présence de plantes pérennes, et en particulier de plantes pérennes en C4 comme le Miscanthus (*Miscanthus* x *giganteus*) ou le switchgrass (*Panicum virgatum L.*) suscite un vif intérêt (Heaton *et al.*, 2008b). Les plantes en C4 possèdent en effet une efficience d'utilisation des ressources en eau et en azote supérieure à celle des plantes en C3. Ces espèces pérennes se caractérisent également par une longue saison de croissance qui permet d'optimiser l'interception du rayonnement et d'obtenir des rendements élevés (Heaton *et al.*, 2008b). Elles sont d'autre part susceptibles d'augmenter la teneur en carbone du sol et pourraient avoir des effets bénéfiques sur la biodiversité puisque le couvert est présent presque toute l'année (Heaton *et al.*, 2008b). L'intérêt de ces cultures se résume donc en une phrase : **elles pourraient permettre d'obtenir une production élevée associée à de faibles impacts sur l'environnement, voire à des impacts positifs**. Elles représentent enfin pour les agriculteurs une possibilité de diversification nécessitant, à l'exception des premières années de culture, peu d'interventions culturales. Leur récolte à la fin de l'hiver, période préférable pour optimiser le recyclage des nutriments par rapport à une récolte à l'automne, est complémentaire avec les autres calendriers de récolte. Le fort investissement nécessaire au moment de la plantation, tout comme leur caractère novateur qui induit un manque d'expérience et une méconnaissance des prix, peuvent toutefois freiner l'adoption de ces cultures par les agriculteurs (Bocquého et Jacquet, 2010).

Les autres ressources candidates possèdent également des intérêts. L'utilisation de plantes entières non dédiées comme le triticale (récolté immature) ou l'ensilage de maïs permet d'augmenter nettement la production de matière sèche à l'hectare par rapport aux cultures mobilisées pour la production de biocarburants 1G. Parmi ces cultures figurent de plus des cultures réputées pour leur rusticité, comme le triticale, ou à haut potentiel environnemental, comme la luzerne. Enfin, l'utilisation des résidus permet de diminuer la concurrence avec la production alimentaire mais peut provoquer des conflits d'usage : les pailles de céréales, par exemple, sont utilisées comme substrat et comme fourrage par les élevages mais aussi comme source de matières organiques pour les sols et pour l'alimentation des animaux d'élevage. A la différence des ressources pérennes, les ressources candidates annuelles et pluriannuelles permettent de construire des systèmes de production beaucoup plus flexibles laissant la possibilité de réduire la production de biocarburants voire de revenir à 100% de production alimentaire dans un scénario prospectif de crise alimentaire mondiale.

1.2.2 Intérêts liés à la diversité des ressources candidates à la production de bioéthanol 2G

La diversité des ressources agricoles candidates à la production de bioéthanol 2G pourrait rendre possible la valorisation de contextes pédoclimatiques variés, voire de milieux dits « marginaux » (sols à faible potentiels, parcelles éloignées des sièges d'exploitations, etc.) ou difficilement valorisables par des cultures alimentaires (ex : sols pollués). La présence de cultures nécessitant peu d'intrants ou à fort intérêt environnemental permet aussi d'envisager leur développement dans des zones à intérêt environnemental (Anex *et al.*, 2007; Cormeau et Gosse, 2007; Sanderson et Adler, 2008; Tilman *et al.*, 2009). C'est le cas par exemple des zones de captage d'eau potable où la mise en culture « continue » par des plantes pérennes permettrait de réduire les risques de lixiviation du nitrate. **La diversité des cultures candidates à la production de biocarburants 2G offre enfin l'opportunité de reconcevoir les systèmes de production agricole pour atteindre une forte efficience énergétique et améliorer leurs fonctions environnementales (Anex et al., 2007; Cormeau et Gosse, 2007).** Or, une reconception des systèmes de culture est jugée nécessaire pour atteindre l'objectif de réduction de 50% des usages de pesticides en France fixé par le Grenelle de l'environnement (Brunet *et al.,* 2009). Enfin, il est envisageable de mettre en place des filières multi-usages où une partie de la culture est destinée à des filières alimentaires humaines ou animales (ex : grains de blé, de triticale, de maïs, feuilles de luzerne) tandis que le reste a une vocation énergétique (ex : pailles de céréales, tiges de luzerne).

L'organisation de nouvelles filières de production de biocarburant 2G à partir de ressources agricoles suscite toutefois des questions importantes. L'augmentation drastique des volumes de production semble être déterminante pour assurer sa viabilité (Bessou *et al.,* 2011). Dans le même temps, on estime qu'un rayon de collecte raisonnable pour une unité moyenne produisant 25 à 50 millions de litres de carburant par an et utilisant 60 000 à 120 000 tonnes de matière sèche par an serait 20 km (IEA, 2008). Produire de tels volumes dans une aire de collecte restreinte limite la contribution des sols marginaux ou des zones à intérêt environnemental à la production de biocarburants 2G. Cela limite également l'opportunité de diversifier les systèmes de culture dans le temps.

1.2.3 Une forte hétérogénéité des niveaux de connaissances associés aux ressources candidates à la production de bioéthanol 2G

Parmi les cultures candidates à la production de biocarburants de deuxième génération, certaines sont déjà couramment cultivées en France. C'est le cas des céréales (blé, orge, triticale, maïs, sorgho), du colza ou de la luzerne. D'autres cultures candidates sont également bien connues dans d'autres régions du monde. C'est le cas du switchgrass couramment cultivé aux Etats-Unis pour produire du fourrage. De même les taillis à courte rotation de saule sont cultivés en Suède depuis les chocs pétroliers des années 70 dans le but de fournir une nouvelle source d'énergie[8] et 16000 ha de TCR sont recensés aujourd'hui dans ce pays. En France, des recherches sur la production de biomasse ligneuse, en particulier à partir de peuplier, ont également débuté à cette période. Près de 400 ha de plantation industrielle de TCR de peuplier à vocation papetière étaient recensés en 1998[9].

En revanche, certaines espèces candidates n'avaient auparavant pas de vocation agricole. C'est le cas du Miscanthus utilisé à l'origine comme plante ornementale. Le genre Miscanthus, originaire d'Asie du Sud-Est, a été introduit en Europe au Danemark dans les années 1920. Les premiers travaux visant à l'utiliser pour la production agricole de bioénergie remontent au début des années 1980. Il a depuis fait l'objet de nombreux travaux expérimentaux en Europe, tandis que les Etats-Unis se sont concentrés sur le switchgrass (Lewandowski *et al.*, 2003a), avant de s'intéresser également au Miscanthus depuis une dizaine d'années.

En 2009, près de 2800 hectares étaient en France occupés par des plantes dédiées (**Tableau 1. 2**). C'est la culture de *Miscanthus* x *giganteus* qui est la plus répandue : à la suite des premières expérimentations installées au début des années 1990, les premiers hectares agricoles ont été plantés entre 2005 et 2006 et on en recense environ 3000 ha aujourd'hui. Les régions les plus concernées en 2009 étaient le Centre (352 ha), l'Ile de France (265 ha), la Bretagne (244 ha), la Champagne-Ardenne (236 ha), la Bourgogne (150 ha), la Picardie (123 ha) et la Basse-Normandie[10]. Notons que ces chiffres évoluent rapidement : en 2012, les surfaces occupées par du miscanthus en Bourgogne avoisinaient ainsi les 470 hectares[11].

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[8] Unasylva - No. 221 - Poplars and willows – Dimitriou and Aronsson 2005 Willows for energy and phytoremediation in Sweden source : http://www.fao.org/docrep/008/a0026e/a0026e11.htm

[9] Biomadi et Berthelot, 2007. Produire de la biomasse avec des taillis de peuplier. FCBA Informations – Forêt, N°4-2007 – Fiche n°760

[10] Agreste, 2009. Statistiques Jachère Industrielle et Aide aux Cultures Energétiques

[11] Chambre régionale d'Agriculture de Bourgogne, Bourgogne Pellets

Figure 1. 3 : *Miscanthus* x *giganteus* à différentes étapes du cycle de culture :

a) quelques semaine après la plantation (mai) b) à la même époque pour une culture de deux ans ; c) fin du printemps pour une culture de trois ans (au premier plan : orge) ; d) début de l'automne pour une culture en première année à gauche et en deuxième année à droite ; e) récolte en bottes d'une culture de trois ans ; f) récolte en vrac d'une culture de trois ans (©Lesur/INRA).

2. *Miscanthus* x *giganteus*: une “nouvelle” culture candidate à la production de biocarburants

Parmi les ressources candidates à la production de biocarburants 2G, *Miscanthus* x *giganteus* suscite un grand intérêt car c’est une culture pérenne en C4. Nous avons d’ailleurs montré que c’est la culture dédiée la plus répandue en France à l’heure actuelle. Il s’agit toutefois d’une culture étudiée depuis peu de temps et nous allons à présent exposer les connaissances disponibles à son sujet.

2.1. Fonctionnement et conduite de la culture

Miscanthus est un genre de plante herbacée pérenne à rhizome de la famille des poacées comportant une dizaine d’espèces. *Miscanthus* x *giganteus* (dénommé ci-après *M. giganteus*) est un hybride spontané entre *Miscanthus sacchariflorus* (4n chromosomes) et *Miscanthus sinensis* (2n chromosomes). Il est donc triploïde ce qui le rend stérile.

Il est planté soit par division des **rhizomes** soit par multiplication végétative, la première méthode étant toutefois, de loin, la plus répandue (DEFRA, 2007). La plantation se déroule à partir de fin mars en France. En parcelle agricole, elle s’effectue à l’aide de planteuses à pomme de terre modifiées ou de planteuses spécialement conçues pour la culture. La première année, le nombre de tiges à l’hectare est faible et la culture ne dépasse pas 250 cm de hauteur : jusqu’aux premières gelées, la culture s’installe et développe en priorité ses organes souterrains (Beale et Long, 1995) (**Figure 1.3a**). Pour des raisons de trop faible biomasse produite en première année, la culture n’est généralement pas récoltée mais broyée pendant l’hiver (Lewandowski *et al.*, 2000).

Les années suivantes, de nouvelles tiges émergent en France entre mi-mars et mi-avril selon les régions (**Figure 1. 3b**). La croissance du couvert, jusqu’à des hauteurs pouvant dépasser 4 m, est presque linéaire de juin à août (Strullu, 2011). Le maximum de biomasse aérienne est atteint mi-octobre (Strullu, 2011) (**Figure 1. 3d**). La biomasse souterraine diminue au printemps avant d’augmenter à nouveau, en raison de l’existence de **phases de translocation/remobilisation entre la partie aérienne et la partie souterraine** (Beale et Long, 1997; Heaton *et al.*, 2009; Strullu *et al.*, 2011) (**Figure 4**). Au printemps, les nutriments contenus dans le rhizome sont utilisés pour la croissance du couvert : les quantités d’azote remobilisées varient entre 25 et 175 kg N ha^{-1} selon les études. A partir du milieu de l’été, la plante transfère une partie des nutriments contenus dans la biomasse aérienne vers les rhizomes. Parallèlement, la partie aérienne entre progressivement en sénescence, les feuilles se dessèchent à partir du bas de la tige avant de tomber les unes après les autres pendant l'hiver. Si le nombre de degrés-jours est suffisant, le couvert fleurit entre mi-septembre et mi-octobre (GIE ARVALIS / ONIDOL, 2010). En France, les plantations du Sud de la France fleurissent chaque année alors que celles du Nord de la France fleurissent occasionnellement (Cadoux, comm. pers.).

La culture peut être récoltée en automne (récolte précoce) ou à la fin de l'hiver (récolte tardive). Si le rendement est supérieur dans le cas d'une récolte précoce, les teneurs en éléments minéraux, notamment en azote et en eau sont plus faibles lors de la récolte tardive (Lewandowski et Heinz, 2003). La récolte tardive est, de plus, privilégiée car elle permet d'optimiser les phénomènes de recyclage des éléments minéraux par le biais de la chute des feuilles et de la translocation entre les parties aériennes et le rhizome. La **récolte** s'effectue en vrac à l'ensileuse ou en bottes avec une faucheuse ou une ensileuse modifiée (*i.e.* une ensileuse qui découpe les tiges en morceaux d'environ 40 cm) (**Figure 1. 3e et 3f**). La voie biochimique comme la voie thermochimique (**Figure 1. 1**) sont envisagées pour produire des biocarburants de deuxième génération. L'efficacité de la voie biochimique dépend des composants de la paroi des cellules végétales (cellulose et hémicellulose) et de leur récalcitrance à la dégradation. L'efficacité de la voie thermochimique augmente pour des taux d'humidité et des contenus en cendres et éléments minéraux faibles (Karp and Shield, 2008).

Le miscanthus est généralement implanté pour une durée de quinze à vingt ans. Les premières années de culture constituent une phase d'établissement pendant laquelle les rendements augmentent. Cette phase peut durer de deux à cinq ans (Lewandowski, 2000, Miguez, 2008). La culture entre ensuite dans une phase où les rendements plafonnent. En Europe, les rendements peuvent atteindre 20 à 50 t MS ha^{-1} an^{-1} en cas de récolte précoce et 10 à 30 t MS ha^{-1} an^{-1} quand la récolte a lieu en fin d'hiver (Clifton-Brown *et al.*, 2000 et 2004 ; Lewandowski, 2000). Les travaux de méta-analyse de Miguez *et al.* (2008) déterminent un rendement maximal moyen de 18,4 t MS ha^{-1} an^{-1} en récolte tardive. Certains auteurs ont observé une troisième phase où les rendements diminuent (Jorgensen, 1996; Clifton-Brown *et al.*, 2007; Christian *et al.*, 2008; Angelini *et al.*, 2009) mais **peu de séries d'évolution à long terme des rendements ont été publiées. Toutes ces références de rendement correspondent de plus à des valeurs expérimentales obtenues sur de très petites surfaces** plantées et récoltées manuellement ou avec du matériel expérimental (généralement 1 à 2 m^2) : elles fournissent d'importantes informations sur le potentiel de rendement de la culture mais **leur généralisation aux conditions agricoles reste limitée** (Heaton *et al.*, 2008b). Il est attendu que le rendement de parcelles agricoles soit moins élevé pour différentes raisons. Ces parcelles, plantées mécaniquement, sont tout d'abord susceptibles de présenter des peuplements plus hétérogènes que les parcelles expérimentales plantées à la main. Les pertes à la récolte pourraient de plus être plus élevées, comme le montrent Monti *et al.*(2009a) pour le switchgrass. **Les conditions agricoles sont enfin vraisemblablement beaucoup plus variables que les conditions expérimentales, qu'il**

s'agisse de la gestion des parcelles ou des caractéristiques du milieu. Ce dernier effet pourrait être d'autant plus fort qu'en raison de la concurrence avec la production alimentaire, les cultures destinées à la production de biocarburants risquent d'être plantées sur des terrains variés, dont certains peuvent être qualifiés de « marginaux ». Le terme marginal, sur lequel nous reviendrons dans le **Chapitre 6** (6.1.3) fait référence ici aussi bien à des parcelles défavorables en raison de leurs propriétés physico-chimiques qu'à des parcelles défavorables en raison de leur forme (surface réduite, nombre d'angles élevé), de leur environnement (proximité d'une rivière, d'un bois, d'une zone à intérêt environnemental, d'un milieu urbain) ou de leur distance importante au siège d'exploitation (ce qui peut amener l'agriculteur à limiter le nombre d'interventions techniques sur la culture).

Les travaux expérimentaux menés à travers l'Europe montrent que les principaux facteurs limitant le rendement de *M. giganteus* sont la **quantité de rayonnement intercepté** (ou encore la proportion de couverture nuageuse), la **température** de l'air et surtout la **disponibilité en eau** (liée à la fois au régime de précipitation et à la capacité de rétention en eau du sol) (Lewandowski *et al.*, 2000, 2003; Clifton-Brown *et al.*, 2004; Heaton *et al.*, 2004; Richter *et al.*, 2008; Pogson, 2011; Maughan *et al.*, 2012a). **Les pratiques culturales mises en œuvre semblent avoir une importance moindre**. Ainsi, la méta-analyse de Miguez *et al.* (2008) conclut à un effet de la densité de semis uniquement lors de la première année de récolte. En matière de **fertilisation azotée,** si une réponse positive a été mise en évidence en cas de récolte précoce, les résultats en récolte tardive sont eux contrastés : sur 14 données expérimentales recensées par Cadoux *et al.* (2012) issues d'expérimentation étudiant l'effet d'une augmentation de la dose d'azote sur le rendement, seules deux correspondent à des situations où l'azote est un facteur limitant du rendement. Ces auteurs en concluent que les besoins de la culture en fertilisation azotée sont faibles. Ceci serait expliqué par (i) une forte efficience d'absorption et d'utilisation des nutriments, (ii) les phénomènes de recyclage entre le rhizome et les parties aériennes, ainsi que par l'intermédiaire de la chute des feuilles avant la récolte (**Figure 4**) et (iii) une possible contribution de bactéries fixatrices d'azote. Les auteurs recommandent une fertilisation minérale n'excédant pas les quantités exportées lors de la récolte, soit environ 70, 10 et 110 kg ha^{-1} de N, P et K respectivement pour un rendement de 15 t MS ha^{-1}. Ils soulignent cependant que la plupart des références disponibles concernent les premières années de croissance de la culture. Les situations où aucun effet de l'augmentation des doses d'azote n'a été observé semblent avoir bénéficié de fortes fournitures d'azote par le sol. Cette observation montre une fois de plus que l'extrapolation de ces résultats aux conditions agricoles est limitée : dans ces dernières, la capacité des sols à fournir de l'azote sera d'autant plus variable, qu'il est envisagé de planter du miscanthus sur des sols dits « marginaux ».

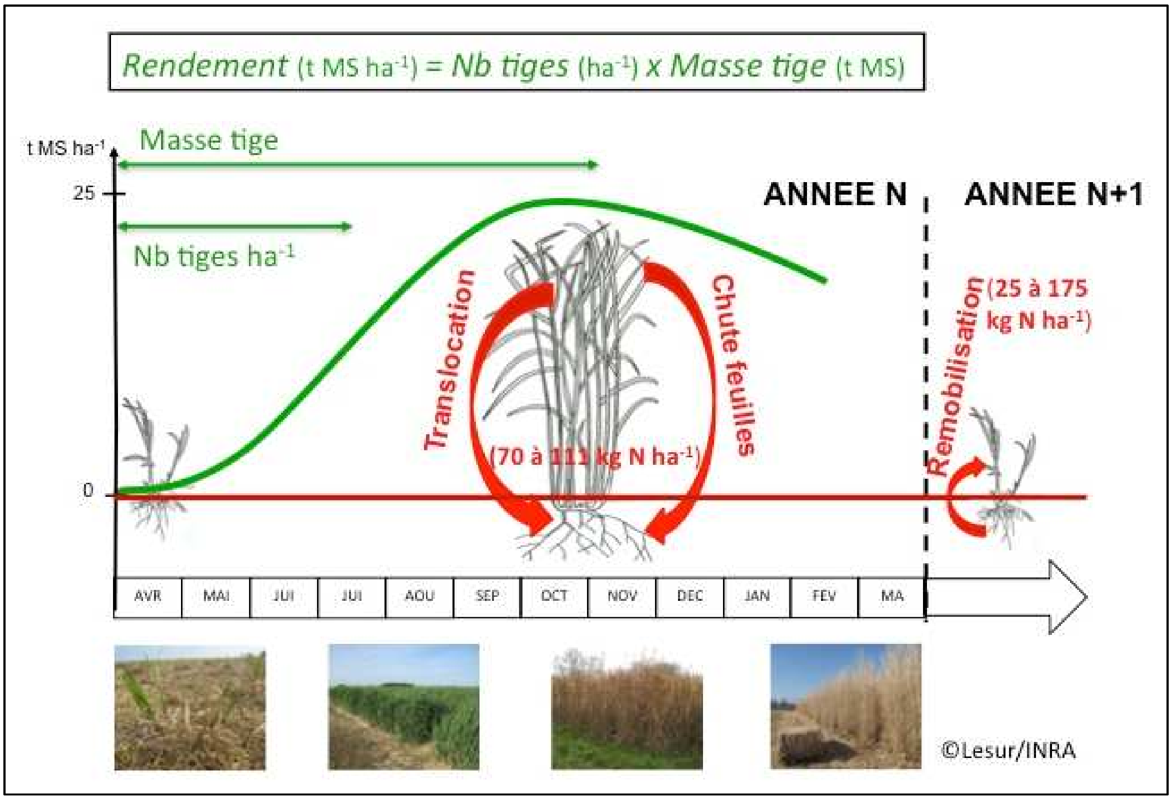

Figure 1. 4 : Ecophysiologie et fonctionnement de *Miscanthus* x *giganteus*
(d'après Beale et Long 1997; Himken et al., 1997; Strullu 2011; Cadoux et al., 2011).

La **gestion du désherbage** constitue une des clés de la réussite de l'implantation (Lewandowski *et al.*, 2000; DEFRA, 2007). Pendant la première année où la culture est très peu concurrentielle vis-à-vis des adventices, les parcelles doivent donc être désherbées chimiquement ou mécaniquement (RMT BIOMASSE, 2012a). Un désherbage chimique avant la reprise de la culture ou mécanique lorsque le couvert est encore clair est nécessaire la deuxième année (RMT BIOMASSE, 2012a). Selon la réussite de l'implantation, il peut encore être recommandé les années suivantes (RMT BIOMASSE, 2012a). Lorsque la culture est bien implantée, la présence d'un mulch important et la couverture rapide du sol au printemps réduisent très fortement le développement des adventices.

2.2. Impacts sur l'environnement

Les faibles besoins de la culture en fertilisation azotée associés à une couverture du sol par la culture en période de drainage hivernal laissent supposer un **faible risque de lixiviation de nitrates**, ce qui a été observé par Christian et Riche (1998) ainsi que Mc Isaac *et al.*(2010). Un faible **risque d'émissions de N_2O** est attendu car la fertilisation azotée constitue le principal facteur d'augmentation des émissions (pour un contexte pédo-climatique donné). Ce dernier point a toutefois fait l'objet d'observations contrastées : Jorgensen *et al.* (1997) ont ainsi mesuré des émissions environs deux fois supérieures à celles associées à une culture d'orge, tandis que celles recensées par Drewer *et al.* (2012) et Gauder *et al.* (2012a) sont inférieures à celles de systèmes de culture à base de cultures annuelles.

Les effets sur la **quantité de carbone séquestrée dans le sol** sont également variables : ainsi, sur les quatre sites étudiés par Kahle *et al.* (2001), deux témoignent d'une augmentation de leur teneur en carbone, tandis que deux ne présentent aucun effet significatif. Ces auteurs ont en revanche démontré des effets positifs sur la matière organique et les propriétés physiques du sol. Malgré des résultats contrastés, il est généralement attendu que la culture joue un rôle de puits de carbone (Hansen *et al.*, 2004; Rowe *et al.*, 2009). **L'étude des impacts sur la biodiversité est très peu développée**. Il semblerait toutefois que la diversité floristique ou faunistique (étudiée pour les oiseaux et les invertébrés) soient moins élevées que pour d'autres cultures lignocellulosiques comme les TCR mais plus élevées que pour des cultures annuelles, surtout lorsque la culture est jeune (Semere et Slater, 2007a; b; Sage *et al.*, 2010).

L'ensemble de ces résultats doit cependant être nuancé car les références disponibles sont dans certains cas très limitées, ne concernent qu'un seul type de pédo-climat ou demandent à être transposées en conditions agricoles. D'autre part, **l'analyse des impacts sur l'environnement doit tenir compte des différentes phases de la culture** décrites au 2.1. Christian et Riche (1998) ont ainsi montré que le risque de lessivage de nitrates peut être très élevé la première année de culture où le couvert est peu développé. De même, Hansen *et al.* (2004) n'ont observé aucune augmentation de la teneur du sol en carbone organique pour une culture de miscanthus âgée de neuf ans comparée aux cultures témoins alors qu'une augmentation a été visible pour une culture âgée de seize ans. De plus, les connaissances sur la destruction du couvert et la remise en culture de la parcelle sont limitées (Cadoux et Ferchaud, 2009) : les premières expérimentations à ce sujet ont eu lieu en France en 2011. Cette étape soulève des interrogations quant aux impacts potentiels sur le milieu, en fonction des méthodes de destruction possibles (chimique et/ou mécanique) et du devenir des nutriments contenus dans le rhizome. La sensibilité des cultures suivantes aux conditions de milieu laissées par *M. giganteus* après sa destruction est également à étudier. **Enfin, l'analyse des impacts environnementaux dépend largement de la situation de référence à laquelle la culture de miscanthus est comparée : celle-ci semble ainsi presque systématiquement plus favorable lorsqu'elle est comparée à des cultures annuelles alors que les résultats sont beaucoup plus mitigés, voire défavorables, lorsqu'elle est mise en regard de prairies ou d'habitats naturels (Rowe *et al.*, 2009)**.

2.3. Travaux d'évaluation menés sur M. giganteus

En raison des exigences réglementaires pesant sur la production de biocarburants, *M. giganteus* fait l'objet de nombreux travaux d'évaluation en mobilisant trois grands types d'approches: (i) l'analyse de cycle de vie (ACV), (ii) l'évaluation à partir de dispositifs expérimentaux et (iii) l'évaluation à partir de modèles.

Sur les 18 travaux recensés ici, sept reposent sur la méthodologie des analyses de cycle de vie (ACV) (Lewandowski et Heinz, 2003; Styles et Jones, 2007, 2008; St. Clair *et al.*, 2008; Monti *et al.*, 2009b; Fazio et Monti, 2011). L'ACV est une méthode d'évaluation des impacts environnementaux potentiels associés à un système de production (dont les contours sont définis lors de la réalisation de l'ACV) par compilation d'un inventaire des entrants et des sortants pertinents pour ce système et évaluation des impacts environnementaux potentiels associés à ces entrants et ces sortants. Le système étudié comprend l'ensemble des phases de la vie du produit, « du berceau à la tombe » : si l'on s'intéresse à un biocarburant issu d'une production agricole, cela implique de réaliser un inventaire des entrants et sortants utilisés pendant la phase de culture, y compris les intrants, mais aussi de ceux associés au transport et au stockage de la culture, puis de ceux mis en jeu lors de la production et de la distribution du carburant. En pratique, la plupart des auteurs restreignent leur étude à une partie du cycle de vie : St. Clair *et al.* (2008) se concentrent ainsi sur les impacts liés à la phase de culture. Les données relatives aux pratiques agricoles et aux rendements sont issues d'expérimentations (Lewandowski *et al.*, 1995; Lewandowski et Heinz, 2003; Monti *et al.*, 2009b; Fazio et Monti, 2011) ou de synthèses régionales (St. Clair *et al.*, 2008). Bien que les ACV puissent prendre en compte des champs d'évaluation variés (changements climatiques, destruction de l'ozone stratosphérique, acidification, eutrophisation, impacts éco-toxicologiques, utilisation des ressources biotiques et abiotiques), les études citées ici se focalisent sur les bilans énergétiques et sur la contribution au réchauffement climatique par le biais des émissions de gaz à effet de serre associées aux cultures étudiées. Notons enfin que Styles et Jones (2008) appliquent le principe de l'ACV pour comparer les performances économiques du miscanthus avec celles des taillis à courte rotation de saule.

Six études évaluent les performances des cultures en calculant des indicateurs à partir de données issues d'expérimentations au champ (Lewandowski et Schmidt, 2006; Clifton-Brown *et al.*, 2007; Boehmel *et al.*, 2008; Heaton *et al.*, 2008a; Angelini *et al.*, 2009). L'échelle d'étude est la parcelle agricole. Les études citées ci-dessus ne prennent en compte que certains champs d'évaluation : Angelini *et al.* (2008) ainsi que Boehmel *et al.* (2008) s'intéressent par exemple aux rendements et aux bilans énergétiques, alors qu'Hallam *et al.* (2001) se limitent aux performances économiques. Lewandowski et Schmidt (2006) et Clifton-Brown *et al.* (2007) ne travaillent que sur le miscanthus, tandis que Boehmel *et al.* (2008) et Angelini *et al.* (2008) comparent différentes espèces. Boehmel *et al.* (2008) comparent de plus pour chaque culture différents itinéraires techniques. L'évaluation de Boehmel *et al.* (2008) présente aussi la particularité de comparer différentes cultures non seulement entre elles (saule, miscanthus, switchgrass, maïs), mais aussi à une succession de cultures à base de colza, de blé et de triticale. Heaton *et al.*(2008a) évalue la surface nécessaire pour produire une quantité de biocarburants donnée à partir de résultats expérimentaux obtenus pour du maïs et du miscanthus.

Les travaux restants, enfin, reposent sur des modèles. Stampfl *et al.*(2007) utilisent le modèle MISCANMOD (Clifton-Brown *et al.*, 2000) pour estimer le potentiel de production de *M. giganteus* à l'échelle européenne. Clifton-Brown *et al.* (2007) s'appuient sur le même modèle pour estimer la quantité de carbone stockée dans le sol pendant la culture de *M. giganteus*. Hastings *et al.* (2009) estime à la fois le potentiel de production et le potentiel de réduction des émissions de gaz à effet de serre en utilisant MISCANFOR, un modèle dérivé de MISCANMOD. Hillier *et al.* (2009) couplent un modèle de rendement (issu de Richter *et al.* 2008) et un modèle simulant l'évolution du stock de carbone du sol (RothC) afin de comparer les émissions de gaz à effet de serre associés à la culture de *M. giganteus* avec celles de trois autres cultures énergétiques (TCR de peuplier, blé d'hiver et colza). Enfin, Ng *et al.* (2010) utilisent le modèle de culture BioCro pour évaluer l'impact de l'introduction de *M. giganteus* dans un bassin versant sur le lessivage de nitrates.

Les résultats issus de l'ensemble de ces travaux sont difficiles à comparer, non seulement en raison des différentes méthodes utilisées, mais aussi en raison des champs d'évaluation qui ne sont pas les mêmes selon les études. De plus, certains de ces travaux sont consacrés uniquement à *M. giganteus* tandis que d'autres comparent la culture soit avec d'autres cultures énergétiques, soit avec des cultures non énergétiques ; certains comparent également l'utilisation de biocarburants produits à partir de *M. giganteus* avec celui produit à partir d'autres ressources agricoles énergétiques, ainsi qu'avec l'utilisation de carburants fossiles. De manière générale, il ressort tout de même de ces études que la culture de *M. giganteus* est nettement plus favorable en termes d'impacts environnementaux et de bilans énergétiques ou gaz à effet de serre que la plupart des cultures annuelles. Si les données relatives à la production de la culture sont bien décrites dans ces études, leur transposition aux conditions agricoles est tout de même limitée car les rendements utilisés sont issus d'expérimentations ou de modèles.

3. Objectif général, questions de recherche et dispositifs d'étude

3.1. Objectif général

Les parties précédentes ont montré que la production de biocarburants à partir de ressources agricoles suscite à la fois espoirs et interrogations. Il existe donc un besoin important d'évaluation *a priori* afin d'informer l'opinion et d'orienter la décision publique. En Europe et en France en particulier, *M. giganteus* est une culture nouvelle qui suscite un vif intérêt. Les travaux entamés ont permis d'améliorer la caractérisation des rendements potentiels, des itinéraires techniques et des impacts environnementaux de la culture. La généralisation des références disponibles aux conditions agricoles est toutefois limitée, ce qui restreint la portée des travaux d'évaluation réalisés. **Par conséquent, l'objectif général de la thèse est (i) de réaliser une évaluation multicritère de systèmes de culture comprenant la culture de *M. giganteus* à partir de données recueillies en parcelles agricoles et (ii) de comparer ces systèmes de culture à des systèmes de culture comprenant d'autres ressources agricoles candidates à la production de biocarburants.**

Un système de culture se définit comme « la nature des cultures, leur ordre de succession et les itinéraires techniques appliqués à ces différentes cultures » (Sebillotte, 1990). A l'échelle du système de culture s'expriment des effets précédents et cumulatifs. Un effet précédent se définit comme « la variation d'états du milieu (caractères biologiques, chimiques et physiques) entre le début et la fin de la culture considérée, sous l'influence combinée du peuplement végétal et des techniques qui lui sont appliquées, l'ensemble étant soumis aux influences climatiques » (Sebillotte, 1990). Un effet cumulatif correspond à la « résultante, sur plusieurs années, des effets précédents » (Sebillotte, 1990). Le système de culture est l'objet d'étude retenu ici pour deux raisons. Tout d'abord, il s'inscrit dans une échelle de temps pluriannuelle, pertinente pour tenir compte de l'ensemble des étapes de la culture de *M. giganteus* : établissement, production et destruction. D'autre part, évaluer cette culture implique de pouvoir la comparer à d'autres ressources agricoles candidates à la production de biocarburants. La diversité des ressources candidates analysées dans la partie 1.2, rend nécessaire d'effectuer cette comparaison à l'échelle du système de culture afin de tenir compte des effets précédents et cumulatifs sur (i) les rendements des cultures (et par conséquent, les bilans économiques et énergétiques associés) et (ii) les impacts sur l'environnement.

3.2. Questions de recherche

Au vu de l'état de l'art sur le fonctionnement de la culture de *M. giganteus* présenté au 2, évaluer des systèmes de culture à base de *M. giganteus* nécessite au préalable d'acquérir des connaissances supplémentaires, en particulier sur le comportement de la culture en parcelles agricoles. Les travaux d'évaluation recensés mettent en effet en évidence que le rendement est une des variables ayant une forte influence sur les performances de la culture (Styles *et al.*, 2008 ; Hillier *et al.*, 2009). Par ailleurs, les valeurs de rendement utilisées sont vraisemblablement souvent surestimées. Il s'agit en effet soit de valeurs expérimentales mesurées pendant les premières années de culture, soit de valeurs issues de modèles de simulation. Le premier sous-objectif de ce travail vise donc à renforcer les connaissances sur les rendements de *M. giganteus* en répondant à la question suivante :

Quelle est la variabilité inter-parcellaire des rendements de *M. giganteus* obtenus en parcelles agricoles et quels sont les facteurs expliquant cette variabilité ?

Cette question fait l'objet du deuxième chapitre de la thèse.

Différentes études ont permis d'étudier l'influence de conditions climatiques très différentes sur le rendement (cf. 2). Nous avons choisi ici d'étudier la variabilité des rendements à l'échelle d'un bassin d'approvisionnement. La variabilité explorée est donc avant tout une variabilité pédologique et non climatique.

L'analyse des références disponibles a également montré que la connaissance des impacts sur l'environnement est fragmentaire et tient peu compte de la variabilité pédoclimatique. La deuxième question à laquelle ce travail cherche à répondre est alors la suivante :

Quelle est la variabilité des impacts de la culture de *M. giganteus* en parcelles agricoles sur la teneur en nitrates dans les eaux de drainage ?

Cette question fait l'objet du troisième chapitre de la thèse et repose sur une analyse des impacts liés à la lixiviation de nitrates. Les enjeux de qualité de l'eau sont particulièrement prégnants en France à l'heure actuelle (Grenelle de l'Environnement, plan Ecophyto 2018). L'implantation de cultures énergétiques pérennes peu gourmandes en intrants est présentée par certains comme un des moyens de maintenir l'activité agricole dans les bassins d'alimentation de captage d'eau potable. D'autres enjeux environnementaux sont bien sûr associés à cette culture, en particulier en termes de gaz à effet de serre et de biodiversité. Les émissions de gaz à effet de serre, dont la quantification est délicate à l'échelle d'un réseau de parcelles agricoles (en particulier pour les émissions de N_20), seront appréciées grâce à des indicateurs (estimés à partir de modèles) dans le chapitre suivant. L'enjeu biodiversité est quant à lui difficilement appréhendable uniquement à l'échelle de la parcelle.

L'état des connaissances que nous avons réalisé plus haut sur le comportement au champ de *M. giganteus* révèle que le rendement ou les risques de lessivage de nitrates ne sont pas les mêmes selon que l'on situe au début du cycle de vie de la culture, lorsque la culture est bien implantée, ou lorsqu'on la détruit. Comme le rendement est un élément clef pour évaluer la durabilité de la culture, la troisième question qui structure ce travail est la suivante :

Comment évoluent les rendements de *M. giganteus* à long-terme, sur l'ensemble du cycle de production ?

Cette question fait l'objet du quatrième chapitre.

Bien que *M. giganteus* soit planté pour des durées supérieures à dix ans, il est nécessaire pour mener une évaluation complète d'intégrer les cultures qui le précèdent et le suivent. Par ailleurs, afin de la comparer avec d'autres stratégies de production de biocarburants à partir de ressources agricoles, il est nécessaire de proposer des systèmes de culture contenant des ressources candidates à cette production, qu'il s'agisse de cultures ou de résidus de culture. La question dont traite le cinquième chapitre est donc :

Quels systèmes de culture contenant *M. giganteus* peut-on proposer ? Quels systèmes de culture incluant d'autres ressources lignocellulosiques peut-on construire ? Quels enseignements tirer d'une évaluation comparée de ces systèmes de culture du point de vue économique, énergétique et environnemental ?

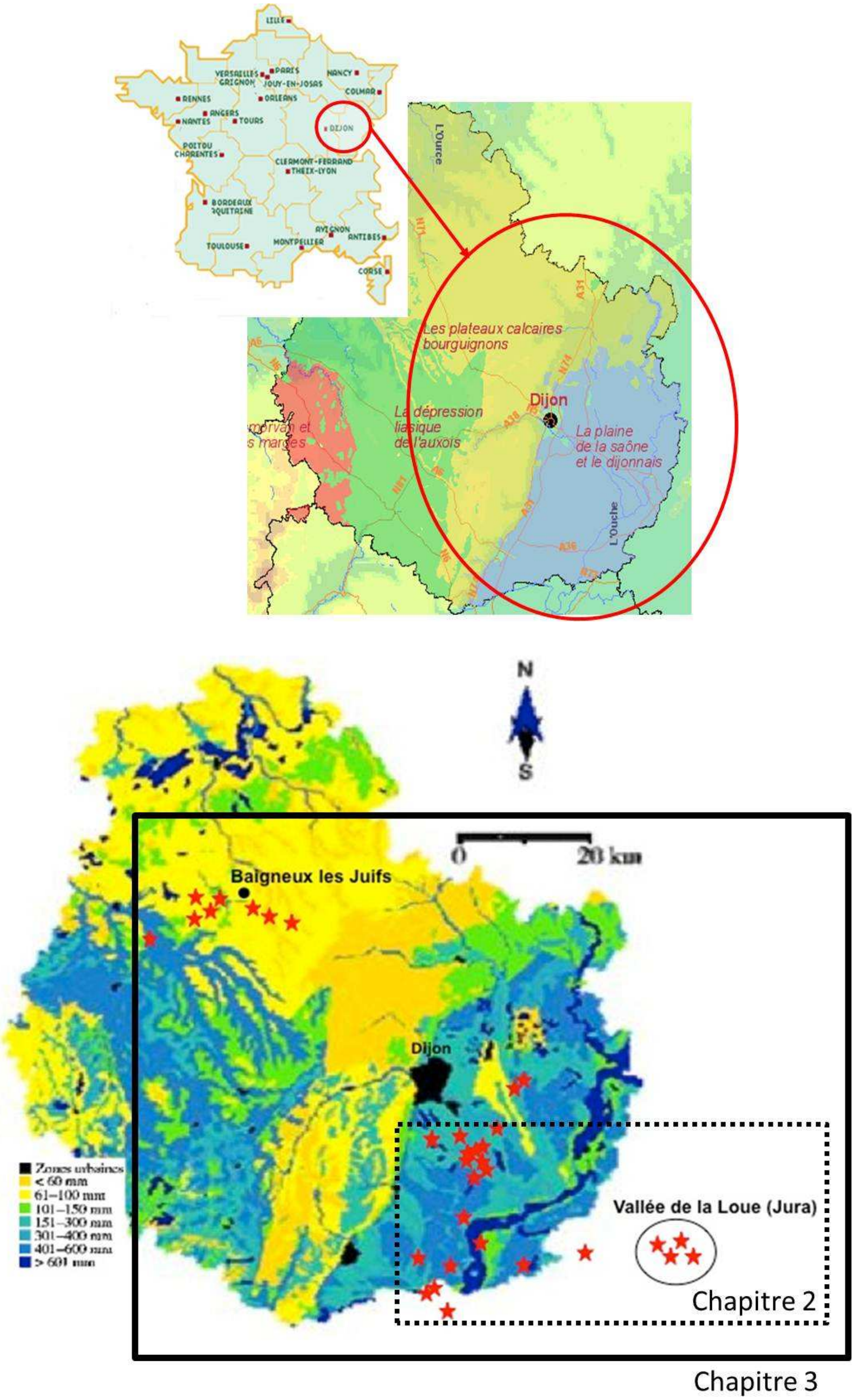

Figure 1. 5 : Localisation du réseau de parcelles agricoles de *Miscanthus* x *giganteus.*

3.3. Dispositifs d'étude

Trois dispositifs d'étude ont été mis en place pour répondre à ces questions.

3.3.1 Etude de la culture de *M. giganteus* en parcelles agricoles

Un réseau de 38 parcelles de *M. giganteus*, plantées en 2009 et 2010, a été mis en place et suivi de 2009 à début 2012. Ce réseau est localisé dans le département de Côte d'Or qui constitue une des zones atelier du projet Futurol (**Figure 1. 4**). Cette région a été choisie comme support de différents travaux de recherche menés dans ce projet du fait :

1. **de la forte dynamique locale observée autour du développement de *M. giganteus* :** en effet, le paysage agricole a été récemment bouleversé par la fermeture de la sucrerie d'Aiserey (21) en 2007 qui a conduit à la suppression des quotas de production de betterave des producteurs de Côte d'Or, Saône-et-Loire et Jura. Suite à cette fermeture, un plan de restructuration « sucre » a été mis en place dans la région. L'un de ses volets consiste à développer une nouvelle filière autour des cultures énergétiques pérennes avec la création en 2008 d'une SICA (Société d'Intérêt Collectif Agricole), nommée Bourgogne Pellets, sur le site de l'ancienne sucrerie, dont l'objectif est en particulier de développer la culture de *M. giganteus*.

2. **de l'existence d'un ensemble important de parcelles agricoles déjà plantées en *M. giganteus* par les agriculteurs (cf. 2.3) ;**

3. **de l'existence d'autres cultures pluriannuelles** (ex : luzerne sur 1200 ha) **et annuelles** (ex : triticale sur 5800 ha) pouvant être utilisées pour la production de biocarburant 2G. Ces deux cultures à vocation aujourd'hui alimentaire constituent des cultures ligno-cellulosiques d'intérêt.

4. **d'un potentiel de diversification des cultures dans le temps de la succession de cultures** : la Côte d'Or est un département dominé par les grandes cultures, qui représentent 60% de la SAU[12] et sont composées à plus de 80% de cultures d'hiver (blé tendre, orge d'hiver et colza). Les protéagineux représentent à peine 0,5% des grandes cultures. La rotation dominante est à base de colza, de blé et d'orge.

5. **de la présence de types de sol variés** : le département de Côte d'Or recouvre quatre grandes régions naturelles (**Figure 1. 4**). Les reliefs du Morvan, à l'Ouest, et le vaste ensemble des terrains calcaires jurassiques, qui forment du nord au sud les plateaux de Bourgogne, constituent deux « hauts pays » entre lesquels s'intercale la dépression liasique périmorvandelle de l'Auxois. Les parties Est et Sud-Est du département sont, quant à elles,

[12] SAU : Surface Agricole Utile

occupées par une zone plus récente d'âge plio-pléistocène, la plaine de la Saône, s'apparentant fortement à la Bresse qui la prolonge vers le Sud. Les parcelles de *M. giganteus* ont été plantées en grande majorité dans la plaine de la Saône, constituée à la fois de limons profonds (> 90 cm) plus ou moins argileux très favorables aux activités agricoles (sols appelés par la suite respectivement LC et C), mais aussi de limons profonds hydromorphes beaucoup plus contraignants (L). Quelques parcelles sont situées sur les plateaux de Bourgogne où dominent des sols argilo-calcaires plus ou moins superficiels (entre 20 et 80 cm) (CC), ou dans des vallées aux sols plus sableux ou riches en graviers (vallée de la Saône et de la Loue) (A).

Ce réseau de parcelles agricoles de *M. giganteus* a été construit en collaboration avec deux partenaires locaux, la coopérative Bourgogne Pellets localisée à Aiserey (21) et la coopérative de déshydratation de luzerne de la Haute Seine, basée à Baigneux-les-Juifs (21). Les parcelles ont été choisies de manière à couvrir la diversité des conditions pédoclimatiques et des systèmes de culture présents dans la région (**Figure 1. 4**). Ainsi, 32 parcelles sont rattachées à la coopérative d'Aiserey et sont localisées en majorité en Côte d'Or (sept sont limitrophes et appartiennent aux départements de la Saône et Loire ou du Jura). Les huit autres parcelles sont rattachées à la coopérative de Baigneux-les-Juifs située sur les plateaux bourguignons dans le nord de la Côte d'Or.

Les objectifs associés à ce dispositif sont :

- **de caractériser la variabilité des rendements en parcelles agricoles et d'identifier les facteurs expliquant cette variabilité à partir d'un sous-échantillon de 20 parcelles localisées dans la zone d'Aiserey (*i.e.* sur les sols argileux C, limono-argileux LC et limoneux hydromorphes L) (Figure 1. 4) (Chapitre 2) ;**
- **d'estimer les risques de pertes en nitrate pendant l'hiver sur l'ensemble des parcelles (Figure 1. 4) ;**
- **de recueillir des données sur les pratiques agricoles pour alimenter l'évaluation économique et énergétique de ces systèmes de culture (Chapitre 5).**

Notons que le réseau de parcelles agricoles contenait initialement 40 parcelles. La plantation de *M. giganteus* a échoué sur deux parcelles situées en sol argilo-calcaire où les mesures n'ont donc été effectuées que pendant un an.

3.3.2 Evolution à long terme des rendements de *M. giganteus* à partir de données expérimentales recueillies à l'échelle Européenne

Dans le but d'étudier l'évolution temporelle des rendements de *M. giganteus*, une base de données rassemblant 42 séries d'évolution (appelées EU ci-dessous) des rendements de *M. giganteus* sur 12 à 22 ans de culture a été construite. Cette base de données, constituée à l'échelle européenne, regroupe 16 sites géographiques différents[13] localisés dans 5 pays, ce qui représente des conditions pédoclimatiques variées : Autriche (5 EU, 5 sites), Danemark (16 EU, 2 sites), France (1 EU, 1 site), Allemagne (9 EU, 3 sites), Irlande (1 EU, 1 site), Royaume-Uni (7 EU, 1 site). Les données rassemblées proviennent de quatre origines différentes : cinq séries sont issues d'articles publiés dans des journaux à comité de lecture, 12 viennent de *proceedings* de congrès, 9 d'un rapport d'un organisme de développement agricole et 16 ont été obtenues par communication personnelle. Il s'agit de rendements recueillis en parcelles expérimentales et non agricoles. En effet, les parcelles agricoles implantées depuis un nombre d'années suffisant et dont les rendements ont été mesurés et référencés avec suffisamment de précisions font défaut. L'approche mobilisée pour traiter ces données consiste à comparer différents modèles d'évolution des rendements en fonction du temps est (**Chapitre 2**).

3.3.3 Conception et évaluation de systèmes de culture comprenant des cultures candidates à la production de biocarburants de deuxième génération

Un dispositif participatif de conception-évaluation de systèmes de culture (Vereijken, 1997; Lançon *et al.*, 2008) a été mis en place dans le but de réaliser une évaluation *ex ante* de systèmes de culture à base de *M. giganteus* et de systèmes de culture contenant d'autres ressources candidates à la production de biocarburants de deuxième génération. La conception des systèmes de culture s'est appuyée sur un atelier de co-conception de systèmes de culture à dire d'experts. L'évaluation des systèmes de culture proposés a reposé sur l'utilisation de modèles, en particulier le modèle de système de culture PerSyst (Guichard *et al.*, submitted, 2010; Annexe 5) et le calcul d'indicateurs. L'évaluation des systèmes de culture à base de miscanthus repose également sur le couplage entre les données recueillies aux **Chapitres 2 et 3** avec des modèles, dont le modèle d'évolution à long-terme des rendements issu du **Chapitre 4**.

[13] Un site géographique peut contenir plusieurs séries d'évolution. Une série (notée EU) correspond au croisement entre un site géographique et un traitement expérimental.

Chapitre 2.

Diagnostic agronomique de la culture de *Miscanthus* x *giganteus* en parcelles agricoles

Ce chapitre correspond à un article qui sera soumis prochainement à Global Change Biology Bioenergy.

Lesur C., Bazot M., Bio-Beri F., Lorin M., Jeuffroy M.H., Loyce C. (to be submitted). Yield gap analysis of young *Miscanthus* x *giganteus* crops: a survey of farmers' fields in centre-east France. *Global Change Biology Bioenergy*

Yield gap analysis of young *Miscanthus* x *giganteus* crops: a survey of farmers' fields in centre-east France

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Abstract

Miscanthus x *giganteus* is often regarded as one of the most promising crops to produce bioenergy because it is renowned for its high yields combined with low-input requirements. However, its productivity has mainly been studied in experimental conditions. Our study aimed at characterizing and explaining *Miscanthus x giganteus* yield variability on a 20 farmers' fields network located in Centre-East France. Our study included the three first growth years of the crop, *i.e.* the two first harvests since the crop was not harvested at the end of the first year. We defined and calculated a set of indicators of limiting factors that could be involved in yield variations and used the mixed-model method to identify those mostly explaining yield variations. We also studied the discrepancy between plot yields measured on a small surface (i.e. two plots of 25 m^2) and commercial yields measured on the whole field. Plot yields averaged 11.2 t DM ha^{-1} for the second growth year and 15.3 t DM ha^{-1} for the third one. Those average results concealed however a high variability: our field network included fields reaching yields close to those reported in experimental conditions (up to 22 t DM ha^{-1}) but also fields with very low yields (below 3 t DM ha^{-1}). Yields were found to be much more related to the shoot density than to the shoot mass. Besides, we highlighted that yields were limited by the shoot density established at the end of the plantation year. Lastly, commercial yields were on average 30% lower than plot yields. Situations specific to commercial farm scale conditions, such as field size or shape, field location and field history were shown to affect the discrepancy between plot yields and commercial yields.

Keywords

Miscanthus x *giganteus*, yield-gap analysis, on-farm research, shoot density, commercial yields

1. Introduction

Miscanthus x *giganteus* (hereafter referred as *M. giganteus*) is a C4 perennial and rhizomateus grass originating from East Asia which has been studied as an energy crop since the mid-1980s, mostly in the European Union (Lewandowski *et al.*, 2003) and more recently in the United States (Heaton *et al.*, 2008). *M. giganteus* rhizomes are planted in spring. As crop production during the first growth year is not sufficient to make harvest profitable, the crop is crushed. From the second year on, the crop is harvested annually. Despite biomass losses during winter, *M. giganteus* uses to be harvested at the end of the winter to improve the combustion quality, to reduce the energy demand for drying (Lewandowski & Heinz, 2003) and to enable nutrient recycling between the above-ground and the below-ground biomass (Strullu *et al.*, 2011; Cadoux *et al.*, 2012). Yields increase during three to five years before reaching a ceiling phase during which a peak productivity is achieved. After establishment, the crop can be harvested annually for 20-25 years (Lewandowski *et al.*, 2003). Crop requirements in terms of nutrients are said to be low thanks to (i) high nutrient absorption and use efficiency and to (ii) nutrient cycling between the above-ground and the below-ground biomass, as well as through leaf fall before harvest. Cadoux *et al.* (2012) recommends a maximum nutrient fertilization of 73.5, 7.0, and 105.0 kg ha^{-1} of N, P and K respectively for a dry matter yield of 15 t ha^{-1} at winter harvest. The crop requires little pesticides as well, except for herbicides during the first two years (Lewandowski *et al.*, 2000).

M. giganteus is often regarded as one of the most promising crops to produce bioenergy and in particular second-generation biofuels because it is renowned for its high yields (Lewandowski *et al.*, 2003; Heaton *et al.*, 2004, 2010; Dohleman & Long, 2009) combined with low-input requirements. High productivity is indeed very desirable for biomass crops since the assessment of several environmental and economic indicators such as energy yield, land area requirement, production cost, gross margin mostly relies on yields. Assessments dedicated to *M. giganteus* were based mostly on yields recorded on small surfaces during field experiments (e.g. 12-30 t DM ha^{-1} when harvested in December; Lewandowski & Heinz, 2003) or from models predicting yields (e.g. 20 t DM ha^{-1} of peak productivity for late winter harvesting; Styles and Jones, 2007); 15-25 t DM ha^{-1} for spring harvesting; Smeets *et al.*, 2009). However, Miguez *et al.* (2008) reported a high between-site yield variability in a meta-analysis on *M. giganteus* yields (with a standard deviation of 4.53 t DM ha^{-1}, for ceiling yields in winter averaging 18.4 t DM ha^{-1}). Besides, sensitivity analyses conducted on yield revealed the strong influence of yield assessment on land requirement (Styles & Jones, 2007), on the crop production costs (Smeets *et al.*, 2009) and profitability (Styles *et al.*, 2008), on the energy yields (Eranki & Dale, 2011) and on the greenhouse gases balance (Hillier *et al.*, 2009; Eranki & Dale, 2011).

Yields recorded in farmers' fields could be quite different from yields recorded in experimental plots due to two factors. First, commercial fields cover a higher range of environments (soil types) and cropping systems (preceding crop, crop management of *M. giganteus*) than experimental fields in which several factors are fixed. Cadoux *et al.* (2012) suggested indeed that the absence of response to increasing nitrogen fertilization observed in several studies is related to high nitrogen (N) soil supply due to the preceding crop or to a significant net N mineralization. In on-farm conditions, nutrient soil supply might be much more variable, as well as water soil supply. As observed in several yield-gap analyses on arable crops (Becker M. & Johnson D.E., 1999; Wopereis *et al.*, 1999; Becker *et al.*, 2003; de Bie, 2004), yields recorded in farmers' fields are lower than the potential yields (limited by solar radiation and temperature only) due to unfavorable growing conditions. Secondly, the assessment of yields in farmers' fields may be lower due to higher harvest losses. The discrepancy between plot and commercial yields was examined by Monti *et al.* (2009a) for switchgrass. To our knowledge, no similar study was carried for *M. giganteus*. The gap between yields measured in experimental and in on-farm conditions might be especially significant for *M. giganteus* since growing the crop on marginal lands is seen as a way to reduce competition with food production.

Our paper aims at characterizing the variability in *M. giganteus* yields in a set of farmers' fields at a regional scale and at identifying the main limiting factors and cropping practices affecting *M. giganteus* yields. We applied the methodology framework of the Regional Agronomic Diagnosis (Doré *et al.*, 1997, 2008) to a field network of young *M. giganteus* grown in the Bourgogne region (located in the Centre-East of France).

We combined a three-step approach. First, we analyzed the variations in yield and yield components observed in the farmers' field network. Then we identified the main limiting factors responsible for yield variation within fields. Finally, we analyzed the relationship between plot yields (measured in the field on small sub-plots) and commercial yields (measured on the whole field) to quantify harvest losses.

Table 2. 1: The farmers' field network

Planting year	Preceding crop	Surface (ha)	Soil type	SWC_{max}[2] (mm)	HUM[2]	Nb of angles[3]	r (width to length)[3]	Dist[4] (km)
2009	Set-aside	1.61	C	228	H	7	>0.20	<10
		2.46	A	53	D	4	≤0.20	>10
		1.59	LC	231	H	4	≤0.20	<10
	Annual Crop	1.31	C	152	-	3	>0.20	<10
		0.75	C	222	H	4	≤0.20	<10
		3.04	C	222	H	6	>0.20	<10
		3.68	C	222	H	5	>0.20	<10
		2.20	LC	207	-	4	>0.20	<10
		1.61	L	225	H	4	≤0.20	<10
		2.07	L	231	H	4	>0.20	<10
2010	Set-aside	2.90	C	226.5	H	8	≤0.20	<10
		0.70	C	228	-	4	≤0.20	<10
		1.54	A	156	-	4	>0.20	<10
		5.50	LC	224	-	10	≤0.20	>10
		1.64	L	221	H	4	≤0.20	<10
		2.30	L	221	H	4	>0.20	>10
		2.99	L	222	H	5	>0.20	<10
	Annual crop	3.35	C	222	H	8	≤0.20	<10
		2.26	A	99	-	4	>0.20	<10
		1.75	A	90	-	5	>0.20	<10

[1] A: alluvial and/or sandy soil; C: clay soil; LC: loamy-clay soil; L: hydromorphic loamy soil.

[2] SWC_{max}: maximal soil water content. HUM: variable describing soil behaviour regarding water (as described by farmers); H = soil with tendency to be wet or even hydromorphic; D = drying soil.

[3] Variables describing field shape: field number of angles and ratio width to length r.

[4] Distance between field and farm.

2. Material and methods

2.1. The farmers' fields network

Data were collected in 20 commercial fields located on 19 farms in the Bourgogne region in France (**Table 2. 1**). Fields were located in a 1500 km^2 area ranging from 46°54' to 47°16' N and from 5°02' to 5°46' E in Centre-East France. The field survey was carried out during three growing seasons between 2009 and 2011, characterized by a hydric deficit[14] of 241, 143, and 276 mm respectively (long-term annual average estimated over the past 20 years: 222 mm). 10 fields were planted in spring 2009 and 10 in spring 2010 after two kinds of preceding crops: (i) annual crops such as wheat, corn, sunflower or (ii) set-aside (for more than five years). Those fields covered four soil types: 3 deep soils (clay soils, clay-loamy soils, hydromorphic loamy soils) and moderately deep soils located on alluvia. Deep soils stood for soils whose depth (estimated through soil core samplings) exceeded 120 cm while moderately deep soils indicated soils whose depth stood between 80 and 110 cm. *M. giganteus* was planted on small fields (from 0.67 to 5.50 ha across fields with an average of 2.35 ha). 12 fields out of 20 displayed an irregular shape (measured by the number of angles) or/and a sharply elongated shape (measured by the ratio of field width to field length). Besides, 13 fields out of 20 were described by the farmers as displaying a problematic behavior regarding water: one field was qualified as prone to water stress while the others were described as wet to hydromorphic. Finally, three fields were located far from the farm.

Fields were planted mechanically with rhizomes at densities varying from 15300 to 22750 rhizomes per hectare in 2009 (mean: 18900 rhizomes ha^{-1}) and from 17400 to 25150 rhizomes per hectare in 2010 (mean: 19650 rhizomes ha^{-1}). More than three quarters of the rhizomes were supplied by ADAS. Analysis on the mitochondrial genome confirmed that all fields had been planted with *M. giganteus*. All fields but one were chemically weeded during the year of establishment, before the first regrowth and occasionally (for four fields) during the second growth year. One field was also weeded before the second regrowth. 18 fields out of 20 were not fertilized. The two remaining fields were fertilized with less than 30 kg N ha^{-1} at the beginning of spring. Due to low biomass production, fields were not harvested at the end of the establishment year but were crushed at the end of December. The years onwards, the whole surface of fields was mechanically harvested from late March to early April in bulk (4 field-years) or in bales (26 field-years).

[14] Hydric deficit = ETP – P, with ETP : sum of evapotranspiration and P : sum of precipitation. Estimated for the whole growing period (April to October).

2.2. Measurements

Measurements were carried out for three crop ages: growth year 1 (GY1), which is the establishment year, growth year 2 (GY2) which is the first harvested year and growth year 3 (GY3).

2.2.1 Growth years 2 and 3

M. giganteus plot yield (pYIELD) was measured in each field at the beginning of February, from the average of two plots of 25 m^2 including six miscanthus rows. Plots were randomly set but precautions were taken to avoid field borders and extreme field areas in term of shoot density (*i.e*. areas that were not representative for the field). Shoot density (SH_DENS) was measured on the whole two plots. 250 shoots were then randomly selected in each plot (from all the rows and different plants), cut approximately 10 cm above ground and weighed. Among them, 20 shoots were subsampled to assess shoot height and shoot diameter. Shoot mass (SH_MASS) was estimated from the mass of 250 shoots. Moisture content of aerial biomass was determined in a sub-sample of around one kilogram.

Weed cover (WEEDS) was assessed on ten 0.25-m^2 micro-plots across the field at the end of winter (March): on each micro-plot, the percentage of weed coverage was estimated visually.

M. giganteus commercial yield (cYIELD) was measured according to the harvest type. When it was harvested in bulk, each truck containing the harvest was weighted and a sample was oven-dried to determine the dry matter rate. When it was harvested in bales, the number of bales per field was counted. Then, an average bale mass per field was estimated by weighing the trailers containing the harvest and the dry matter rate was determined with the help of a probe.

2.2.2 Establishment year

Fields were not harvested at the end of the first growth year but were crushed. One 50-m^2 plot was set and observed twice a year. The density of emerged rhizomes was measured at the end of June (RH_DENS), when emergence was considered as over. That density was used along with planting density to estimate the emergence rate (E_RATE) *i.e.* the ratio between RH_DENS and planting density. Shoot density at the end of the first growth year (SH_DENS_1) was measured before crushing. Ratio between SH_DENS_1 and RH_DENS was defined as the tillering rate (T_RATE). Weed cover (WEEDS_1) was assessed visually at the end of the winter using the same method than during GY2 and GY3.

2.2.3 Soil and climatic data

Weather data such as mean temperature (T), global radiation (Rg) and potential evapotranspiration (ETP) were collected from two Meteo France stations (Ouges, 5°04'41'' E – 47°15'38'' N, and Chamblanc, 5°04'41'' E – 47°15'38'' N) and from a third station set up in Chissey sur Loue (5°44'12" E – 47°01'37'' N). Each field was connected to the closest station that was located at 20 km maximum.

Soils were characterized from local experts and soil analyses. 15 soil cores were collected across each field until a depth of 120 cm maximum with a hydraulic coring device (for shallower soils, the sampling depth matched soil depth). Each core was split into four layers (0-30, 30-60, 60-90, 90-120 cm) and four soil samples were obtained by mixing the 15 cores. The sample coming from the 0-30 cm layer was analyzed to determine particle size and chemical composition: assimilate P (method Olsen), exchangeable Mg and K, total carbon and nitrogen, CaCO3 and pH. Samples from the 30-60, 60-90 and 90-120 cm layers were mixed and particle size was determined on the mixture result. Maximum rooting depth according to soil type and crop age was assessed on nine contrasting fields with a soil profile and extrapolated on the other fields belonging to the same category: maximum rooting depth was set to 120 cm for *M. giganteus* crops older than one year and planted on deep soils, while it was reduced to 80 cm for one-year-old crops. On shallower soils, maximum rooting depth was estimated as the maximum sampling depth. Particle size and maximum rooting depth were combined to estimate maximal soil water content (SWC_{MAX}) according to the Jamagne method (Jamagne, 1968).

2.3. Variation analysis in plot yield and plot yield components

Variation in plot yield (pYIELD) was first described and analyzed according to yield components in three steps. First, analyses were carried out within each harvested year and pYIELD was related to its components (SH_DENS and SH_MASS). Then, each variable estimated for a given year, pYIELD, SH_DENS and SH_MASS, was related to the same variable estimated the preceding year to study how one growth year impacted the following one. Finally, a focus was made on the establishment year. The impact on the shoot density established at the end of the establishment year (SH_DENS_1) on the following years was assessed. Variation in SH_DENS_1 was analyzed through its components: the emergence rate (E_RATE) and the tillering rate (T_RATE). All analyses were performed thanks to variance analyses. The relationship between yield and shoot density was also analyzed with a non-linear model to determine the threshold above which yield did not increase anymore. All statistical analyses were carried out with the statistical program R (version R-2.13.1).

2.4. Defining indicators of limiting factors

Several indicators of limiting factors were defined both for harvested growth years (that is to say growth years 2 and 3) and for the establishment year.

2.4.1 Growth years 2 and 3

Water balance

The dynamic water balance was calculated on a daily basis as follows:

$$SWC(j) = R(j) + I(j) + SWC(j-1) - ETR(j) - D(j)$$

With:
SWC(j): Soil Water Content at day j (mm)
R(j): amount of rainfall at day j (mm);
I(j): daily amount of irrigation at day j, zero in our study (mm)
ETR(j): actual evapotranspiration at day j (mm)
D(j): amount of drainage at day j, assumed to be equal to zero in our study (mm).

Water balance was initialized on March 1st under the assumption that SWC at that date was equal to SWC_{MAX} (*i.e.* the soil was at water capacity). As *M. giganteus* is a perennial crop, from the second growth year on, the root system is already developed when the first shoots emerged in spring. We therefore assumed maximal rooting depth (and as a consequence SWC_{MAX}) to be constant during the growing season.

ETR was defined as follows:

$$ETR(j) = Ks(j) * Kc(j) * ETP(j)$$

With:
ETP(j): potential evapotranspiration at day j;
Kc(j): cultural crop coefficient at day j defined as a function of degree-days (Audoire, 2011; data from the French multilocal experimental network REGIX) from the sugarcane Kc as defined by the FAO (Allen *et al.*, 1998);
Ks(j): stress coefficient at day j; Ks(j)=1 if SWC(j)>=2/3*SWC_{MAX} and Ks(j)=SWC(j) / SWC_{MAX} (Itier, 1996).

An indicator assessing the intensity of water deficit was derived from (3) and (4) on a daily basis as follows:

$$WATER(j) = \frac{ETR(j)}{Kc(j) * ETP(j)} = Ks(j)$$

It was then averaged on the time period defined for each yield component. For SH_DENS, we assumed by expertise that all effective shoots (which excludes regressive shoots) are established at the end of May so we calculated $WATER_{EP}$ from emergence (~ March 25th) until May the 31th. For YIELD, $WATER_{GP}$ was calculated over the whole growing period, *i.e.* from emergence until first frosts (~ October 15th).

Nitrogen from mineralization

As most crops were not fertilized, an indicator on the nitrogen available to the crop was assessed by estimating the quantity of nitrogen mineralized from humus (Mh) using the following equations adapted from the Azodyn model (Jeuffroy and Recous, 1999)and the COMIFER method (COMIFER, 2011):

$$Mh = TNorg * Km * ND$$

With:
TNorg: humified organic nitrogen stock of the mineralising layer (t organic N ha^{-1})
Km: humified organic nitrogen mineralisation rate (kg mineral N / (t organic N * ND))
ND: number of normalised days during a given period of time

$$TNorg = Nt * P * Da * (100 - SR)/100$$

With:
Nt: organic nitrogen rate of the mineralising layer fine earth (%)
P: mineralising layer depth (cm)
Da: fine earth apparent density of the mineralising layer
SR: stony rate in the mineralising layer (%)

$$Km = Km_{sd} * F_{syst}$$

With:
Km_{sd}: standard humified organic nitrogen mineralization rate
F_{syst}: increase factor of the quickly mineralisable organic nitrogen pool under the influence of the cropping system organic restitution mode. F_{syst} was set up to 1 in our study.

$$Km_{sd} = 22750/((110 + A) * (600 + CaCO_3))$$

With:
A: clay rate of the mineralising layer (g/kg)
$CaCO_3$: limestone rate of the mineralising layer (g/kg)

ND was computed as a function of mean temperature and soil humidity using the following equation:

$$ND = \sum_{j} \exp\big(K * (T(j) - Tref)\big) * Ks(j)$$

With:
K: coefficient temperature equal to 0,115 (Jeuffroy and Recous, 1999)
T(j): mean temperature on day j (°C)
Tref: reference temperature equal to 15°C (COMIFER, 2011)
Ks(j): water stress coefficient computed on day j following the water balance

Mh_{EP} and Mh_{GP} were computed differently for SH_DENS, SH_MASS and YIELDS using the same time periods than those used for both WATER indicators.

Weeds

The indicator related to weed cover (WEEDS) was defined as the mean of the measurement described in 2.2.

Shoot density of the establishment year and crop age

SH_DENS_1 and crop age (AGE) were chosen as proxy variables to take into account the perennial character of the crop: the crop development a given year has indeed consequences on the development on the crop the year after through the nutrient translocation between the aerial biomass and the rhizome described by Beale and Long (1997) and Strullu *et al.*(2011).

2.4.2 Establishment year

The same indicators of limiting factors were calculated to characterize the establishment year through the shoot density established at the end of the year (SH_DENS_1) and the tillering rate (T_RATE). The water balance computation was however slightly different. First, as the crop above-ground biomass development is postponed and reduced compared to the following growth years, we defined by expertise crop coefficients adapted to the establishment years. Besides, contrary to growth year 2 and 3, we cannot assume maximal rooting depth to be constant during the first growing season: we assumed that rooting depth increased from 20 to the establishment year maximal rooting depth (80 cm, as defined in 2.2). For SH_DENS_1, $WATER_{1\text{-}GP}$ was computed on the whole growing period from the plantation date (~April 1st) to the first frosts (~October 15th). For T_RATE, $WATER_{1\text{-}TR}$ was computed from July 1st to October 15th assuming that emergence was over at the end of June.

2.5. Selection of indicators of limiting factors explaining yield and yield component variations

Indicators of limiting factors involved in yield and yield component variations were identified with a three-step method. First, yield and yield components were successively related to the candidate explanatory variables using linear regression models defined by $y = \varphi_0 + \varphi_1 x_1 + \ldots + \varphi_p x_p + \varepsilon$ where y is the response variable (pYIELD, SH_DENS or SH_MASS), $x_1, \ldots, x_p$ are the explanatory variables (indicators of the limiting factors) and ε is the residual error term. The mixed-model method (Burnham & Anderson, 2002) was used to select the explanatory variables $x_1, \ldots, x_p$ and to estimate the model parameters $\varphi_0, \ldots, \varphi_p$. The mixed-model method, already used by Casagrande *et al.* (2009) to identify the main factors limiting the grain protein content of organic winter wheat, consists in fitting all possible linear combinations of the explanatory variables by least square and in computing, for each combination, the Akaïke Information Criterion (AIC) value (Akaike, 1974) and the Akaïke weight (Burnham & Anderson, 2002).

The Akaïke weight was computed for each regression models as:

$$w_i = \frac{e^{-0.5(AIC_i - AIC_{min})}}{\sum_{i=1}^{n} e^{-0.5(AIC_i - AIC_{min})}}$$

Where w_i is the weight obtained for the *i*th combination of explanatory variables, AIC_i is the AIC value computed for the corresponding model, and AIC_{min} is the minimal AIC value obtained among all the possible combinations.

The weight w_i is the probability that, given a set of models, model *i* would be the AIC-best model (Burnham & Anderson, 2002). The relative importance of the variable *x* is then estimated by $w_+(x)$, the sum of the Akaïke weights across all models in the set where this variable occurs. The larger $w_+(x)$, the more important *x* is (Burnham & Anderson, 2002). The mixed-model method was computed using the package MMIX of the R statistical software (Morfin & Makowski, 2009).

In a second step, stability of the mixed-model method results was assessed using bootstrapping method, as described by Prost *et al.* (2008) to identify and rank the limiting factors of wheat yield. The principle of bootstrap is to generate a large number of new datasets from the initial dataset by randomly sampling data with replacement. 1000 bootstrap samples were generated from the initial dataset and the mixed-model method was applied on each sample using the package MMIX of the R statistical software (Morfin & Makowski, 2009). For each explanatory variable were computed (i) the frequency of selection of each variable across the bootstrap samples, (ii) the mean of the estimated parameters values across the bootstrap samples and (iii) the standard deviation of the estimated parameter values across the bootstrap samples.

2.6. Identification of field and cropping systems characteristics explaining weed cover during the establishment year

Finally, the selected limiting factors for the establishment year were related to the field environmental conditions and to the cropping systems characteristics. For each selected limiting factors, we defined a set of field cropping systems characteristics likely to have an impact on the selected factor. For instance, regarded weed cover, we selected six variables which were likely to induce a higher weed pressure or to have an impact on the efficiency of weed management. DIST represented the distance between the field and the farm. Two variables characterized the field shape: SURF for the field surface and ANGL for the field number of angles. PREC gave information on the preceding crop. HUM indicated the tendency of the soil to be wet or even hydromorphic. Variables describing weed management (based on herbicide applications) were not included because we could not assess whether the timing of herbicide application was appropriate or whether herbicide treatments were efficient, and thus relate weed management to weed cover. Variables were defined as binary and rules defining their levels are defined in **Table 2. 5**.

For each previously identified limiting factors, a k-means cluster analysis (Jain & Dubes, 1988) was implemented to identify groups of fields standing for contrasting levels of the limiting factor. The clustering algorithm is based on a sum-of-squares estimation and attempts to group the fields increasing cluster internal homogeneity and external or between-group heterogeneity. The number of clusters (i.e. groups of fields with similar values of a given limiting factor) was set after assessing the evolution of the least sum-of-squares as a function of the cluster number. Then, each variable likely to influence the studied limiting factor was used as an explanatory variable in a classification tree algorithm to identify the variables that discriminated the k-means clusters. A classification tree is the collection of many rules displayed in the form of a binary tree. The classification tree is built following the process described by Therneau and Atkinson (1997). Basically, to begin with, a single explanatory variable is found which best splits the data into two groups. The data are separated, and then this process is applied separately to each sub-group, and so on recursively until the subgroups either reach a minimum size (here 2) or until no improvement can be made.

2.7. Analysing yield gaps between plot yields and commercial yields

The discrepancy between commercial yields and plot yields was displayed graphically and the gap between both yields (C-P YIELD GAP) was computed as the variation rate between plot yields and commercial yields as follows:

$$C - P\ YIELD\ GAP = \ (pYIELD - mYIELD)/mYIELD$$

We hypothesized that the C-P YIELD GAP could be due to (i) harvest losses and (ii) measurement methods. Factors likely to cause harvest losses were defined by expertise as: the harvest type (bulk or bales) (HARV), the field surface (SURF) and the field number of angles (ANGL). We assumed that the main sources of measurement error regarding plot yields was the field heterogeneity (HET) estimated from the replicates. Regarding commercial yields, we also assumed that fields with a low ratio between width and length were likely to display a higher discrepancy between plot yield and machine yield since the border effect is proportionally stronger on such fields. Those variables were qualitatively defined following the rules described in **Table 2. 6**. The influence of each variable likely to influence C-P YIELD GAP was assessed graphically.

Table 2. 2: Variance analysis on yield –for growth years 2 and 3

	p-value		partial r^2
SH_DENS	$1.7*10^{-15}$	***	0.61
SH_MASS	$1.6*10^{-12}$	***	0.31
AGE	0.054	*	0.07
SH_DENS*SH_MASS	$1.4*10^{-4}$	***	0.03
SH_DENS*AGE	0.34		0
SH_MASS*AGE	0.73		0
SH_DENS*SH_MASS*AGE	0.90		0
		total r^2	0.96

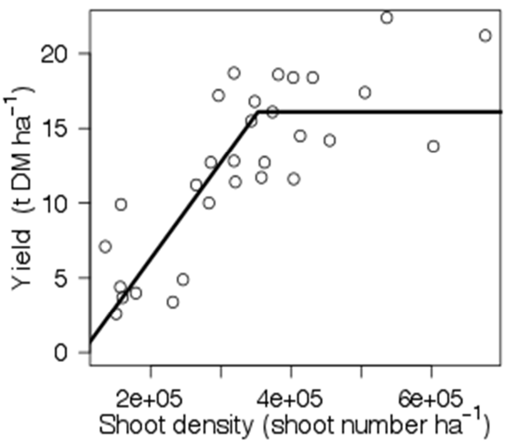

Figure 2. 1: Variation in yield as a function of shoot density for growth years 2 and 3.

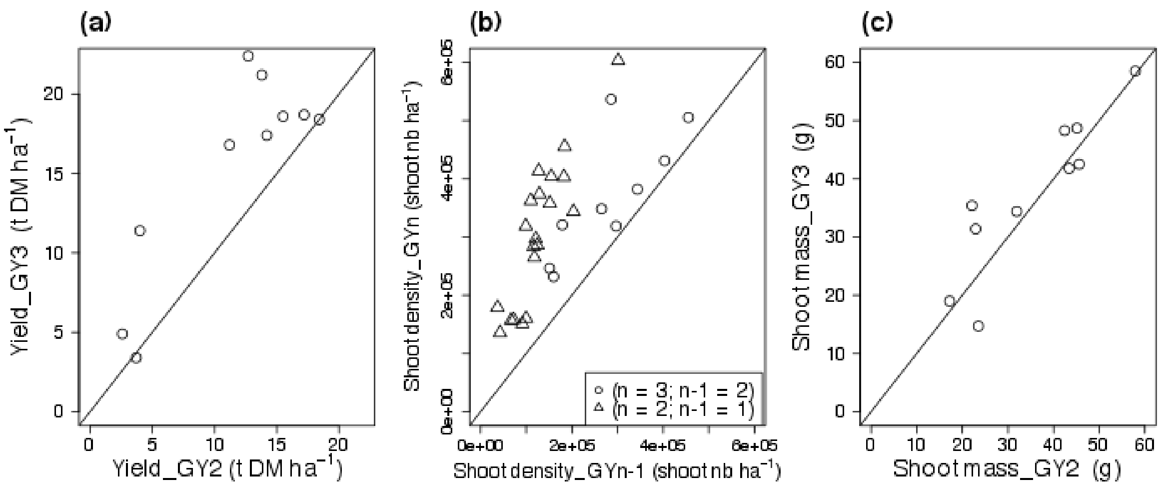

Figure 2. 2: Inter-annual relationships between a) yields, b) shoot densities and c) shoot masses.

Circles stand for *M. giganteus* fields with n = GY3 and n-1 = GY2 whereas triangles stand for M. giganteus fields with n = GY2 and n-1 = GY1. Straight line stands for the 1:1 line.

3. Results

3.1. Variations in plot yield and plot yield components

3.3.1 Relationship between yield and yield components within one year

Plot yield (pYIELD) was highly variable in this network of farmers' fields, ranging from 2.6 t DM ha^{-1} to 22.4 t DM ha^{-1} and averaged 12.6 t DM ha^{-1}. pYIELD depended more strongly on the shoot density (SH_DENS) (p-value < 0.001 and partial r^2=0.63) than on the shoot mass (SH_MASS) (p-value < 0.001 and partial r^2=0.32) (**Table 2. 2**). It depended as well on an interaction between shoot density and shoot mass. To a lesser extent, pYIELD depended on crop age: on the 10 fields where yield was measured during the second growth year (GY2) and the third growth year (GY3), it averaged 11.2 t DM ha^{-1} for GY2 (range: 2.6–18.4 t DM ha^{-1}) and 15.3 t DM ha^{-1} for GY3 (range: 3.4–22.4 t DM ha^{-1}). Yield was also related to the shoot height (p-value < 0.001 and partial r^2=0.52) but was not related to the shoot diameter (data not shown).pYIELD increased with shoot density until a threshold estimated around 390 000 shoots m^{-2} (**Figure 2. 1**).

3.3.2 Relationship between yield and yield from two successive years

pYIELD reached at the end of GY3 was strongly related to the one of GY2 (p-value < 0.001, r^2=0.74; **Figure 2. 2a**). Yield components were also highly dependent from one growth year to the subsequent growth year: r^2 reached 0.62 for shoot density (p-value < 0.001) and 0.78 for shoot mass (p-value < 0.001) (**Figures 2. 2b and 2c respectively**). Shoot density increased more between GY1 and GY2 than between GY2 and GY3 as shown on **Figure 2. 2b** while shoot mass remained stable between GY2 and GY3 (**Figure 2. 2c**).

3.3.3 Yield components of the first growth year

Shoot density established at the end of the first growth year (SH_DENS_1) was not statistically related to the emerged rhizome density measured at the end of June (RH_DENS) (p-value > 0.5) (**Figure 2. 3a**). Shoot density depended slightly on the emergence rate (E_RATE) (p-value < 0.001, r^2=0.17) (**Figure 2. 3b**), but depended very strongly on the tillering rate (T_RATE) (p-value < 0.001, r^2=0.81) (**Figure 2. 3c**). The interaction between emergence rate and tillering rate was not significant. **Figure 2. 3d** highlights that fields with similar emergence rates (for instance about 0.75) were characterized by highly variable tillering rates (ranging from 3 to almost 12 shoots per emerged rhizomes in the example).

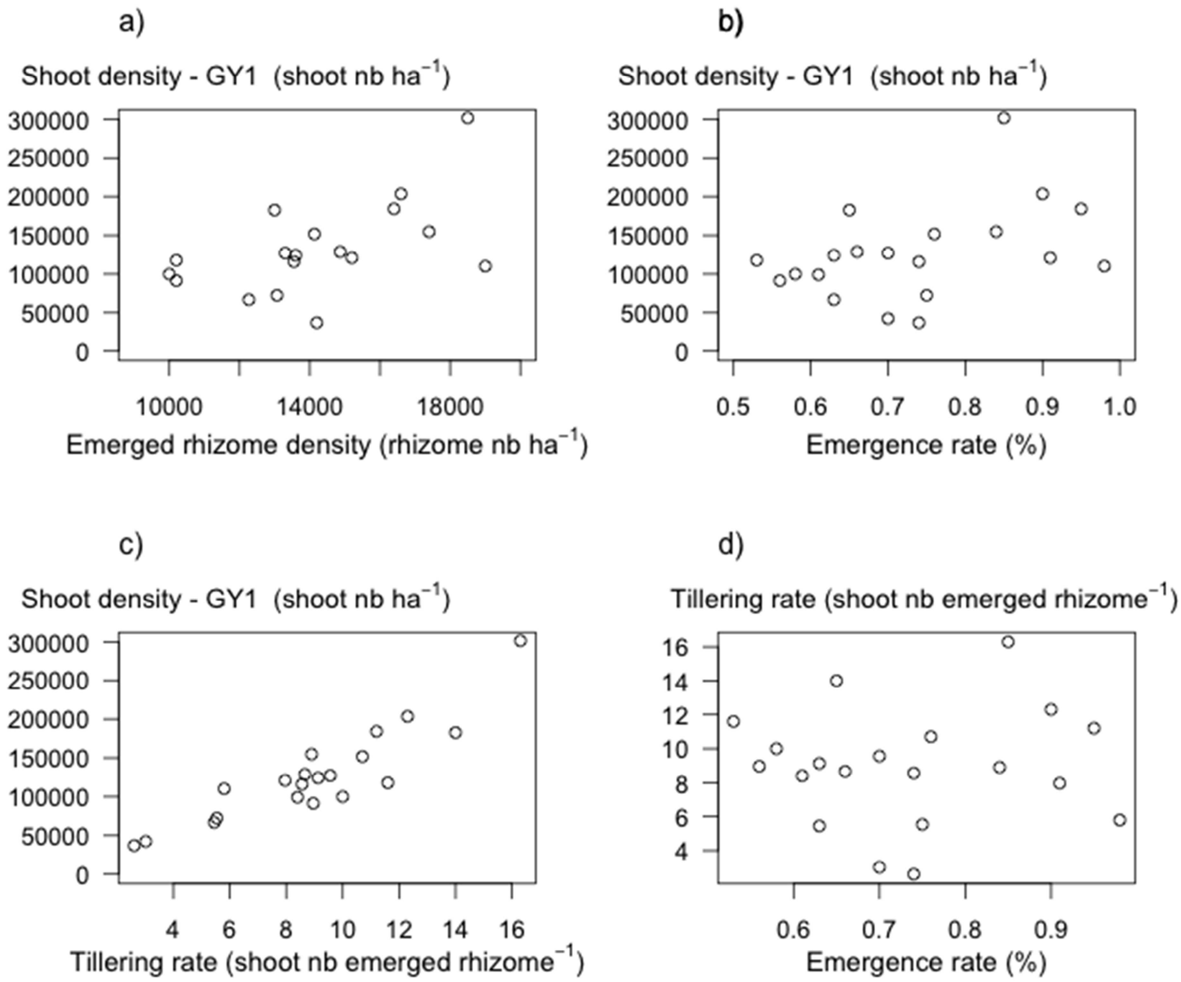

Figure 2. 3: Variations in components measured during GY1. Shoot density measured at the end of GY1 as a function of a) emerged rhizome density, b) emergence rate and c) tillering rate; d) tillering rate as a function of emergence rate.

3.2. Identification of yield limiting factors during the first two harvested years

Identification of limiting factors was carried out successively on yield (pYIELD), shoot density (SH_DENS) and on shoot mass (SH_MASS) (**Table 2. 3**). Estimated parameter values and standard deviations were similar before and after the bootstrap procedure so we displayed only the parameter values computed after bootstrap. On the opposite, we displayed the relative importance values computed before and after bootstrap.

For pYIELD, the factors associated with the highest relative importance values were SH_DENS_1 and WEEDS: w_+(SH_DENS_1) amounted 0.91 while w_+(WEEDS) was equal to 0.92. With w_+(AGE) equal to 0.74, AGE had also some influence. On the other hand, $WATER_{GP}$ and Mh_{GP} had the lowest relative importance values (0.45 and 0.43 respectively). The probability that these factors appeared in the best model was thus low and they were assumed to have little effect on pYIELD. However, $w_+(WATER_{GP})$ and $w_+(Mh_{GP})$ were smaller before the bootstrap procedure, highlighting that the results for those variables were sensitive to variations in the sample data. The range of value for $WATER_{GP}$ was large (from 0.4 to 1) but $WATER_{GP}$ values lower than 0.65 were recorded in only six field-years. Besides, field-year with similar values for $WATER_{GP}$ (respectively for Mh_{GP}) were associated with totally different values for YIELD highlighting that other limiting factors had much more impact.

For SH_DENS, SH_DENS_1 was the limiting factor associated with the highest relative importance value: with w+(SH_DENS_1) equal to 1 before and after the bootstrap procedure, that limiting factor was always selected and did not depend on the sample data. w+(WEEDS) amounted 0.72 highlighting the strong relationship between WEEDS and SH_DENS. With w+(AGE), w+($WATER_{SP}$) and w+(Mh_{SP}) equal to 0.58, 0.52 and 0.60 respectively, AGE and Mh_{SP} were slightly related with SH_DENS.

3.3. Identification of limiting factors occurring during the establishment year

The influence of limiting factors was analyzed on the shoot density established at the end of the first growth year (SH_DENS_1) and on the component that had the biggest influence on SH_DENS_1: the tillering rate (T_RATE) (**Table 2. 4**). On SH_DENS_1 as on T_RATE, w_+(WEEDS) amounted respectively 0.77 and 0.65 and was the only factor that had a high relative importance value. $w_+(WATER_{1GP})$ and $w_+(WATER_{1TR})$ were equal respectively to 0.46 and 0.52 making the variable WATER dependent on the on-farm design, as Mh ($w_+(Mh_{1GP})$ = 0.57 and $w_+(Mh_{1TR})$ = 0.45).

Table 2. 3: Identification of the factors explaining yield variability

Limiting factors	YIELD				SHOOT DENSITY			
	Parameter value	Standard deviation	Relative importance value $w_+(x)$		Parameter value	Standard deviation	Relative importance value $w_+(x)$	
	after bootstrap		before bootstrap	after bootstrap	after bootstrap		before bootstrap	after bootstrap
AGE	2.97	2.15	0.88	0.74	$3.03*10^4$	$3.38*10^4$	0.61	0.58
WATER*	-0.767	7.90	0.30	0.45	$-7.34*10^4$	$1.46*10^5$	0.44	0.52
Mh*	-0.00757	0.0398	0.29	0.43	$1.60*10^2$	$2.10*10^3$	0.60	0.60
Shoot density 1	$3.78*10^{-5}$	$1.63*10^{-5}$	0.98	0.91	1.59	0.228	1	1
WEEDS	-0.324	0.200	0.97	0.92	$-4.70*10^3$	$3.42*10^3$	0.76	0.81

* According to the explained variable, WATER and Mh were computed on different periods of time.

Table 2. 4: Identification of the factors explaining the variability of shoot density and of tillering rate established during growth year one

Limiting factors	SHOOT DENSITY_1				TILLERING RATE			
	Parameter value	Standard. deviation	Relative importance value $w_+(x)$		Parameter value	Standard. deviation	Relative importance value $w_+(x)$	
	after bootstrap		before bootstrap	after bootstrap	after bootstrap		before bootstrap	after bootstrap
Mh	$9.95*10^2$	$1.26*10^3$	0.39	0.57	0.0680	0.0992	0.33	0.45
WATER*	$-5.82*10^2$	$9.37*10^2$	0.31	0.46	-0.0265	0.0658	0.27	0.52
WEEDS	$-9.33*10^2$	$7.26*10^2$	0.70	0.77	-0.0403	0.0398	0.55	0.65

* According to the explained variable, WATER was computed on different periods of time.

Fields were divided into three groups according to the value of WEEDS by the k-mean analysis. Group 1 gathered the 12 fields with the lowest weed cover (mean = 3.9%). The six fields present in group 2 were characterized by medium weed cover averaging 28%. Two fields had extreme weed cover value amounting 92% and formed group 3. Tree classification highlighted that DIST was the first splitting variable (**Figure 2. 5**): the two fields located the furthest from the farm (49 and 13 km) were the one belonging to group 3, *i.e.* the group with the most extreme weed cover values. Then, HUM and PREC interacted: most fields of group 2 were wet fields that had been left as set-aside lands for more than five years before *M. giganteus* was planted. SURF took part in the splitting process but did not influence weed cover. Three fields out of 20 were described as 'difficult to manage' by the farmers. If that variable was added to the classification tree, it became the second splitting criteria after DIST.

3.4. From plot yields to commercial yields

Commercial yields were strongly related to plot yields (p-value < 0.01, $r^2 = 0.72$) (**Figure 2. 6**). The discrepancy between commercial yields and plot yields was however higher when plot yields increased. Three groups of yield gap intensity were defined by the k-mean analysis. Group 1 gathered the 13 fields with the lowest yield gap which averaged 12.2%. Fields in group 2 (14) were characterized by a medium yield gap of 44.6%. Group 3 held only 3 fields but, with an average of 88.7%, they were associated to the highest yield gap. Graphical analysis suggested that small fields, fields with very irregular shapes (number of angles > 6) and fields harvested in bales tended to have higher discrepancy between plot yield and commercial yield, suggesting that these factors induced higher harvest losses (**Figure 2. 7a, b, c**). Cutting height had no impact (data not shown). Fields with low ratio width to length (< 0.2) displayed higher yield gaps as well, suggesting that yield estimation from plot yields on these fields was less accurate due to the higher part of the field suffering from border effect (**Figure 2. 7d**). Yield gap was higher when a farmer owned several fields, confirming that commercial yields were then estimated with less accuracy (**Figure 2. 7e**). On the opposite, field heterogeneity estimated from the plot yield replicates did not seem to affect the discrepancy between plot yields and commercial yields (data not shown). However, variability in each variable level was large and no statistical analysis was conclusive.

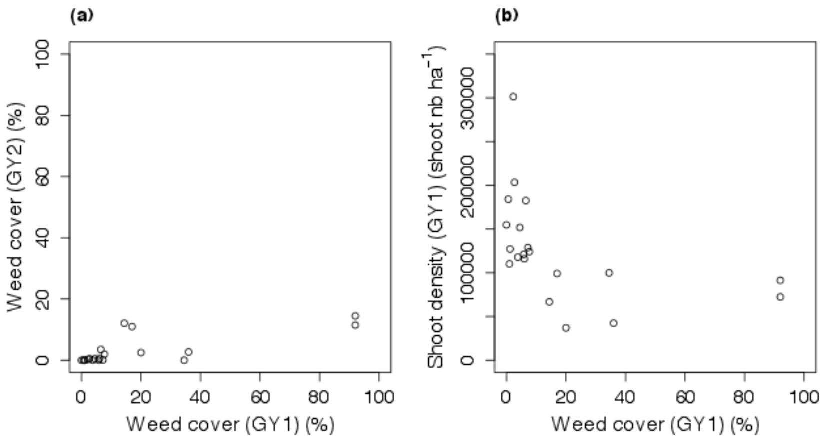

Figure 2. 4: Influence of weed cover: a) evolution of weed cover between growth year 1 and growth year 2; b) shoot density as a function of weed cover at the end of GY1.

Table 2. 5: Rules defining the value of the factors influencing weed cover

Factor	Level	Value
Field distance to the farm	<10km >10km	0 1
Field surface	>= 2 ha < 2 ha	0 1
Field number of angles	= 4 ≠ 4	0 1
Preceding crop	Arable crop Set-aside	0 1
Soil humidity	Normal Tendency to be humid or hydromorphic	0 1

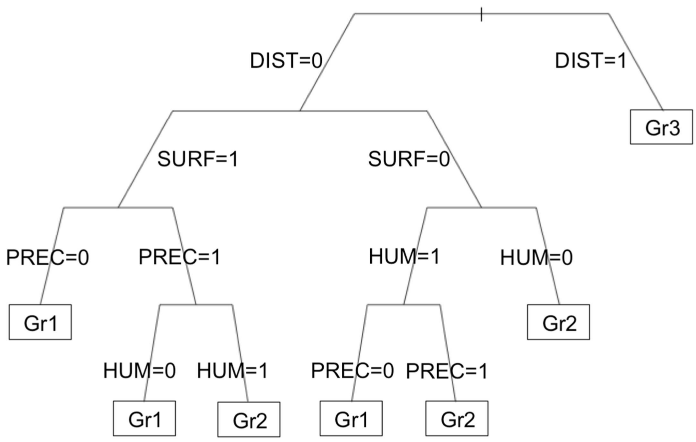

Figure 2. 5: Classification tree of the factors related to the weed cover measured at the end of the establishment year.

Boxes indicate terminal nodes with a majority of members of one group (Gr1: low weed cover; Gr2: intermediate weed cover; Gr3: high weed cover)

4. Discussion

4.1. Are yields overestimated in assessments dedicated to *M. giganteus*?

Plot yields measured in our farmers' fields network averaged 11.2 t DM ha^{-1} for the second growth year, which is similar to the mean yield predicted with the statistical model derived from the meta-analysis of Miguez *et al.* (2008) (*i.e.* 12.6 t DM ha^{-1}). For the third growth year, plot yields averaged 15.3 t DM ha^{-1} for the third one, *i.e.* a lower value than the 18.1 t DM ha^{-1} derived from Miguez *et al.* (2008). In the same way, the average plot yield value we measured for the second growth year was intermediate between low average yields measured in different experiments – 3 t DM ha^{-1} in England (Riche *et al.*, 2008), 4.8 t DM ha^{-1} in Northern France (Zub *et al.*, 2011), 5.5 t DM ha^{-1} in Germany (Clifton-Brown & Lewandowski, 2002) and 8 t DM ha^{-1} in Austria (Schwarz, 1993)– and high average yields measured in Poland (15.3 t DM ha^{-1}; Jezowski *et al.*, 2011) or in the United States (16.5 t DM ha^{-1}; Maughan *et al.*, 2012). On the opposite, third year yields reported in the experiments mentioned here above (16, 18.5, 22, 24 t DM ha^{-1}, in Germany, United States, Austria and Poland respectively) were higher than the one we observed except for England (11.6 t DM ha^{-1}; Riche *et al.*, 2008). Besides these average values, it has to be noticed that we observed high yield variability: plot yields varied from 2.6 to 18.4 t DM ha^{-1} for the second year and 3.4 to 22.4 t DM ha^{-1} for the third one. This variability is higher than the one observed on seven sites with contrasted soil water availability located in England: Price *et al.*(2004) indeed measured second year yields ranging from about 2 to 8 t DM ha^{-1} and third year yields ranging from about 5 to 15 t DM ha^{-1}.

As Clifton-Brown *et al.* (2001), Jezowski *et al.* (2011), Zub *et al.* (2011) and Gauder *et al.*, (2012), we found that yields were strongly related to shoot density. We observed a mean shoot density of 400 000 shoots ha^{-1} for the third year, associated as for yields to a high variability ranging from 232 000 to 677 000 shoots ha^{-1}. On average, shoot densities reported in the literature are higher than the mean shoot density and even the highest shoot densities observed in our study. Except Maughan *et al.* (2012) who reported a mean density of 570 000 shoots ha^{-1}, Clifton-Brown and Lewandowski (2002), Jezowski *et al.* (2011) and Zub *et al.* (2011) reported indeed densities of 650 000, 739 000 and 740 000 shoots ha^{-1} respectively. Besides, fields studied here were characterized by an important planting heterogeneity: several fields include areas with very few plants, and sometimes any plant at all. This is different from experiments where missing plants are commonly replaced after the plantation year, as described by Clifton-Brown and Lewandowksi (2002), Clifton-Brown *et al.* (2007), Maughan *et al.* (2012). On one field out of twenty, rhizomes were even mechanically divided

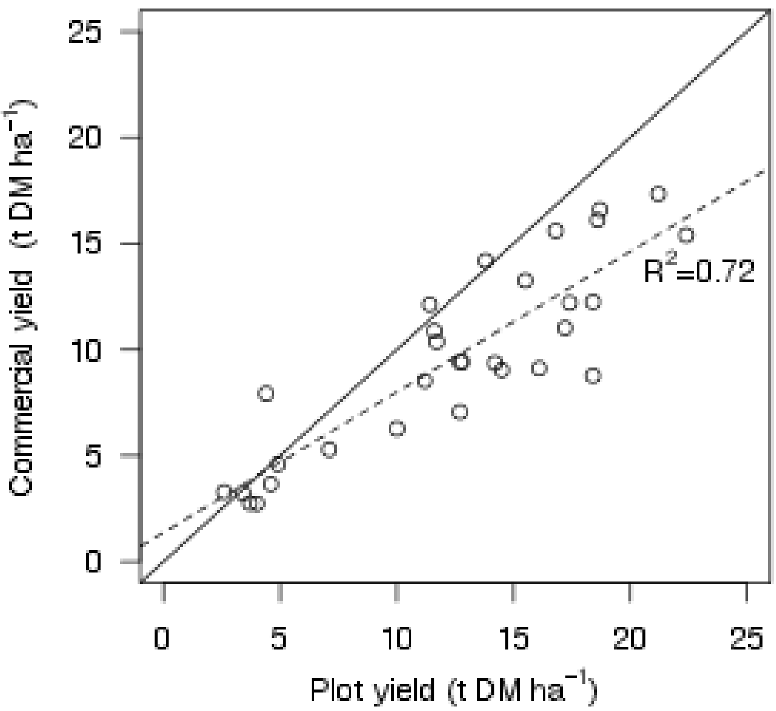

Figure 2. 6: Relationship between commercial yields and plot yields.

at the end of the first winter in the hope of reducing planting heterogeneity and increasing plant density.

Following Jezowksi *et al.* (2011) and Zub *et al.* (2011), we can regard yields measured in the third growth year in our farmers' field network as a good indicator of *M. giganteus* yield potential. On the basis of the comparisons here above, we can estimate that yield estimations commonly used in assessments dedicated to *M. giganteus* – e.g. 12-30 t DM ha^{-1} for Lewandowski and Heinz (2003), 20 t DM ha^{-1} for Styles and Jones (2007), 15-25 t DM ha^{-1} for Smeets *et al.* (2009) – tend to be overestimated compared to farmers' fields yields, especially regarding the highest estimations. Besides, the discrepancy between plot yields and commercial yields was until now strongly underestimated: we highlighted that commercial yields were on average 30% lower than plot yields whereas Lewandowski and Heinz (2003) assumed indeed that harvest losses represented 1.5% of dry matter of plot yield and Monti *et al.* (2009b) considered that yields measured under field conditions were 15% lower than yields under experimental plots. Styles *et al*. (2008) were closer from our observations since they assumed that standing yield amounted to 20 t DM ha^{-1} and combustible yield to 14 t DM ha^{-1}. Lastly, given the large yield variability observed between fields, the use of several assumptions on *M. giganteus* yields should be generalized in the assessments dedicated to the crop.

4.2. What are the main yield limiting factors identified in on-farm conditions?

In our on-farm network of young *M. giganteus* fields, we highlighted that yields were strongly limited by the shoot density established at the end of the first growth year: plantation success appears therefore to be decisive. Young *M. giganteus* crops characterized by a poor establishment hardly recover in the following growth years. We also found yield variability to be significantly explained by weed cover. Similarly, we showed that the shoot density of the first growth year was strongly related to the tillering rate, and that variability of both variables was explained by weed cover. As weed competition with early growth of *M. giganteus* was not monitored from the beginning of the growth season, it is difficult to conclude whether weed pressure decreased yields or whether lower biomass enabled weed development. Our network included fields characterized by high or even extreme weed cover at the end of the establishment year (e.g. 35%, 44%, 92%, **Figure 2. 4**). On most fields, weed cover decreased strongly from the second year on: *M. giganteus* crushing at the end of the plantation year allowed the development of mulch, which was fed by the leaves falling during autumn and winter the years after. However, fields with the highest weed cover at the end of the plantation year displayed also the highest weed cover the years after (**Figure 2. 4**). As *M. giganteus* is known for being poorly competitive with weeds during the establishment year

Table 2. 6: Rules defining the value of the factors influencing the gap between commercial yields and plot yields

Factor	Level	Value
Harvest type (HARV)	Bulk Bales	0 1
Field surface (SURF)	≥ 2 ha < 2 ha	0 1
Field number of angles (ANGL)	= 3, 4, 5 ≥ 6	0 1
Field heterogeneity (HET)	Variation rate between pYIELD replicates < 20% Variation rate between pYIELD replicates > 20%	0 1
Ratio width / length (WIDTH)	>0.2 ≤ 0.2	0 1

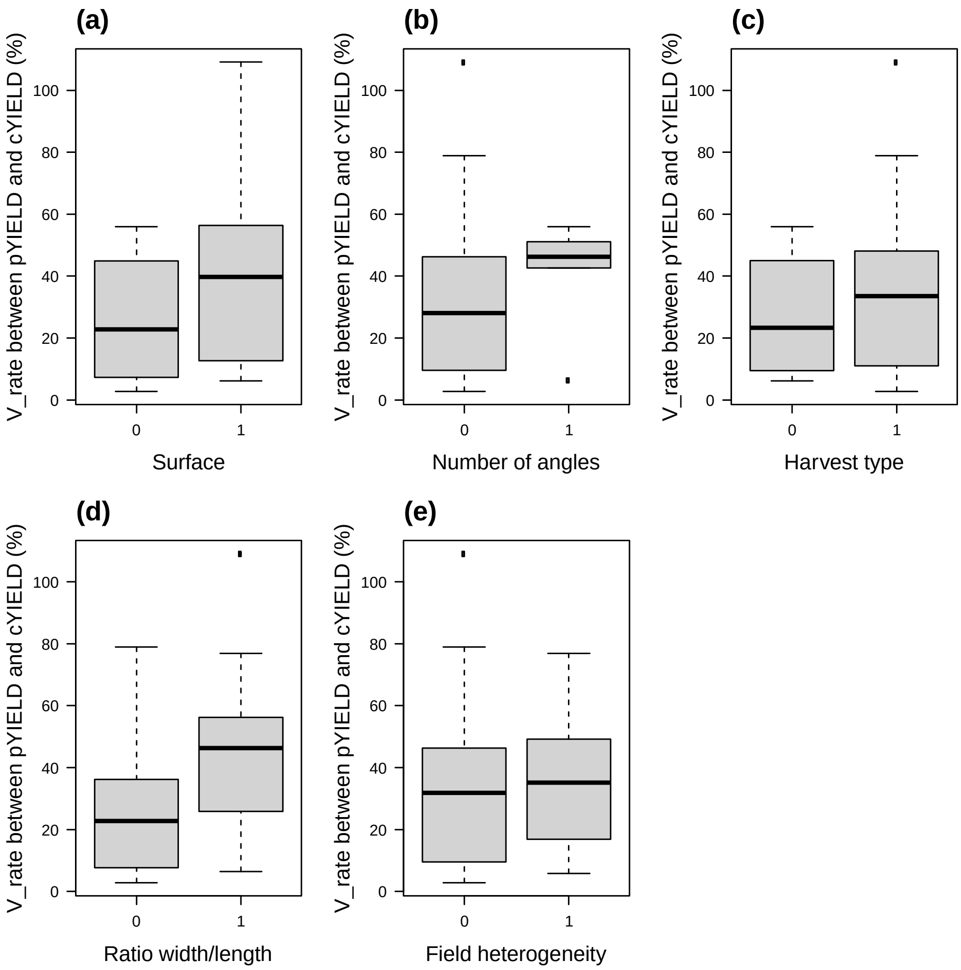

Figure 2. 7:Variation rate (V_rate) between plot yield and commercial yield as a function of: a) Field surface; b) Field number of angles; c) Harvest type; d) Field ratio width/length; e) Field heterogeneity

(Lewandowski *et al.* 2000), we assume that on the fields with the highest weed density, weeds limited shoot tillering during the first year. We also hypothesized that the weed effect highlighted the years after by the limiting factor selection procedure resulted from an interaction between the poor shoot development and the high weed development, which occurred during the plantation year.

In experimental conditions, several authors reported that *M. giganteus* yields were limited by water availability. Comparing *M. giganteus* and *Panicum virgatum* on the basis of 21 papers, Heaton *et al.* (2004) found that the first crop showed a stronger response to water, while the second one was more sensitive to nitrogen. Richter *et al.*(2008)showed that, at the United-Kingdom scale, *M. giganteus* yields were limited by available soil water capacity, air temperature and precipitation. On a single experiment carried out for thirteen years in Germany, Gauder *et al.* (2012) highlighted that yields were correlated to precipitation and concluded that most years, yields were limited by water availability. On our farmers' field network, we did not find yields to be limited by water availability. It is probably due to the fact that most fields displayed high soil water capacity (mean=193 mm; range: 42 – 228 mm). Only three fields out of 20 were characterized by soil water capacity lower than 100 mm. Two of these three fields were located on alluvial gravel soils close to river and probably benefited from high ground-water level. The last one belongs to the two fields characterized by the lowest shoot densities and by the lowest yields. Compared to Heaton *et al.* (2004) and Richter *et al.* (2008), we explored a narrow spatial climatic variability since our fields were located in the same supply area, while, compared to Gauder *et al.*(2012), we explored a narrow temporal weather variability. Comparison with long-term climatic averages highlights that the years included in our study were characterised by hydric deficits only slightly higher (241 and 276 mm in 2009 and 2011 respectively) or even lower (143 mm in 2010) than the mean value estimated over 20 years (222 mm).On the other hand, as we estimated the water stress indicator adapting a water balance model commonly used for annual (Sinclair & Ludlow, 1986; Muchow & Sinclair, 1991; Lecoeur & Sinclair, 1996; Soltani *et al.*, 2000) and perennial crops (Lacape *et al.*, 1998; Pellegrino *et al.*, 2005), it would be valuable to assess the validity of this indicator for *M. giganteus*. Further research is also needed to characterize the crop sensitivity to water stress according to the growth stage and to relate soil water deficit to vegetative growth. Finally, the weight of the plantation success might have concealed the influence of limiting factors impacting at the annual scale.

4.4. Cropping *M. giganteus* on marginal lands?

Cropping *M. giganteus* on marginal lands appears as a way to limit the concurrence between food crops and non-food crops. Although marginal lands are not clearly defined (Batidzirai *et al.*, 2012), according to the CGIAR, they can refer to lands concerned by biophysical (drying soil, water saturated soil, etc.) or socio-economic constraints (land legal status, remote field, etc.) (CGIAR, 1999). In our study, we highlighted that fields with the highest weed development were commonly located far from the farm or seen as 'difficult to manage' by the farmers. Those fields were left for many years as set-aside lands before the plantation of *M. giganteus* and except one, their soil had a tendency to be wet or even hydromorphic: they combined high weed seed banks and physical conditions in favor of weed development. Besides, they display high click beetle pressure, which can decrease emergence rates if it is not managed (Béjot, pers. comm.). Interviews with the farmers showed that they chose those fields to plant *M. giganteus* because the crop was described as a way to cultivate fields that were left as set-aside lands, located in environmentally-sensitive areas or fields that are difficult to manage due to their size, shape or environment in order to decrease the competition of energy crops with food production. However, results of our study underlined that such marginal lands may require special care during the establishment phase (particularly regarding weed management). Besides, our study suggested that small fields and/or fields with irregular shape could display a higher risk of harvest losses, reducing the production potential of that type of marginal lands. Bulk harvest also seemed to induce lower harvest losses than bale harvest. In our study, the distance between the field and the transformation plant determined harvest type since transport costs are higher for *M. giganteus* harvested in bulk. However, we could not assess which factors affected the most the discrepancy between plot yield and commercial yield. Further research on harvest losses could therefore be valuable.

5. Conclusion

M. giganteus plot yields averaged 11.2 t DM ha^{-1} after the second growth year and 15.3 t DM ha^{-1} after the third one but were associated to a high variability since they ranged from 2.6 and 3.4 t DM ha^{-1} (for the second and third year respectively) to 18.4 and 22.4 t DM ha^{-1}. Yields were much more related to the shoot density than to the shoot mass. Yields were strongly limited by the shoot density established during the first growth year. The lowest yields were also related to high weed cover. Characteristics such as distance from the farm, preceding crops and soil humidity appeared to influence weed cover. Field size and field shape impacted harvest losses, which were estimated to amount 30% of plot yields. Those results highlighted that growing young *M. giganteus* on farmers' involves limiting factors different from those commonly reported in the literature in experimental conditions. We thus provided interesting findings to feed assessments dedicated to *M. giganteus* and to stimulate the discussions about growing bioenergy crops on marginal lands.

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Chapitre 3.

Estimation du lessivage de nitrates sous la culture de *Miscanthus* x *giganteus*

Ce chapitre correspond à un article accepté par Global Change Biology Bioenergy en décembre 2012.

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Assessing nitrate leaching during the three first years of *Miscanthus* x *giganteus* from on-farm measurements and modeling

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Abstract

Miscanthus x *giganteus* is often regarded as one of the most promising crops to produce sustainable bioenergy. This perennial crop, renowned for its high productivity associated with low input requirements, in particular regarding fertilisers, is thought to have low environmental impacts, but few data are available to confirm this. Our study aimed at assessing nitrate leaching from *Miscanthus* x *giganteus* crops in farmers' fields, thus including a wide range of soil and cropping system conditions. We focused on the first years of growth after planting, since experimental studies have suggested that *Miscanthus* x *giganteus*, once established, results in low nitrate leaching. We combined on-farm measurements and modeling to estimate drainage, leached nitrogen and nitrate concentration in drainage water in38 fields located in Centre-East France during two winters (November 2010-March 2011, November 2011-March 2012).

Nitrate leaching and nitrate concentration in drainage water were on average very low. Nitrate leaching averaged 6 kg N ha^{-1} while nitrate concentration averaged 12 mg l^{-1}. These low values are attributable to the low estimates of drainage water (mean= 166 mm) but also to the low soil mineral nitrogen contents measured at the beginning of winter (mean = 37 kg N ha^{-1}). Our results were however very variable, mainly due to the crop age: nitrate leaching and nitrate concentration were critically higher during the winter following the first growth year of *Miscanthus* x *giganteus*, reflecting the low development of the crop. This variability was also explained by the range of soil and cropping conditions explored in the on-farm design: shallow and/or sandy soils as well as fields where establishment failed had a higher risk of nitrate leaching.

Keywords

Miscanthus x *giganteus*, nitrate losses, on-farm research, soil mineral nitrogen

1. Introduction

Miscanthus x *giganteus* (hereafter referred to as *M. giganteus*) is often regarded as one of the most promising crops to produce biomass for bioenergy (Lewandowski *et al.* 2000, 2003; Heaton *et al.* 2004, 2008a, 2008b, 2010; Hastings *et al.* 2008, 2009). This tall C4 perennial rhizomatous grass from Asia is well-known for producing high yields with low fertilizer and pesticide inputs and its long lifespan(Lewandowski *et al.* 2000; Heaton *et al.* 2004; Miguez *et al.* 2008; Dohleman & Long 2009). It is therefore expected to have lower environmental impacts than annual crops (Powlson *et al.* 2005; Rowe *et al.* 2009; Heaton *et al.* 2010), particularly regarding nitrogen (N) losses in the environment. However, studies assessing the exact amount of nitrogen lost in the form of N_2O, NH_3 and NOx emissions or nitrate leaching in groundwater are scarce. N losses are still an important consideration when appraising the overall sustainability of producing bioenergy from *M. giganteus*.

Decreasing the risk of nitrate leaching involves better management of the nitrogen cycle, increasing the use of available nitrogen by crops and reducing soil nitrogen content at the beginning of winter. Fertilizer requirements of *M. giganteus* are less than for other crops (Beale & Long 1997; Cadoux *et al.* 2012). Compared to annual crops (most of which are harvested during summer), *M. giganteus* can still take up mineral nitrogen during autumn, before the period of heavy rainfall and/or low evapotranspiration (in the ecological conditions prevailing in Europe) *i.e.* when the risk of leaching increases. This late N uptake (associated with the uptake of water over a longer period than for annual crops) as well as the extensive rooting system of the crop (Neukirchen *et al.* 1999; Monti & Zatta 2009) could then limit the risk of nitrate leaching during the winter (Powlson *et al.* 2005; Rowe *et al.* 2009).

However, few references are available on this aspect. Beale and Long (1997) examined nitrate leaching over a year with deep drainage lysimeters under a three-year-old *M. giganteus* crop and measured nitrate concentrations averaging 17.7 mg l^{-1}. Christian and Riche (1998) studied nitrogen leaching with porous cups during the three first growth years and found that leaching was low when *M. giganteus* was unfertilized, except during the first winter following planting, when N losses were almost ten times greater than those measured in the following years. In the same experiment, Christian *et al.* (2008) observed a ten-year mean leaching of 22.4, 26.7 and 62.9 kg N ha^{-1} when *M. giganteus* received 0, 60 and 120 kg N ha^{-1} respectively. This experiment also suggested a higher risk of N leaching during the year following crop establishment. McIsaac *et al.* (2010) observed with lysimeters that annual nitrate losses from unfertilized *M. giganteus* were similar to those observed in unfertilized switchgrass (*Panicum virgatum*) and far smaller than under maize (fertilized with 168 or 202 kg N ha^{-1}) rotated with unfertilized soybean. Smith *et al.* (2013) highlighted with tile drains and resin lysimeters that nitrate leaching in *M. giganteus* decreased with crop age but decreased more slowly in case of establishment problem.

All these experiments provide information on N leaching but do not cover the range of environmental conditions and cropping systems where *M. giganteus* might be grown. In particular, they do not account for the variable soil, climatic and growing situations existing in agricultural conditions. They are based on lysimeters, drained perimeters or ceramic cups, which provide direct measurements of nitrate fluxes and/or water fluxes but cannot be installed on a wide range of sites. Soil cores provide information on soil nitrogen and water contents but not on fluxes. Standard crop models can predict water and nitrogen fluxes below the rooting zone but they require many data to be parameterised with good accuracy and their predictive capacity is often poorly characterised. However, nitrate leaching simulation models such as LIXIM (Mary *et al.* 1999) allow water and mineral N measurements to be converted into water and nitrate fluxes and are well adapted to account for variable soil, climatic and growing situations. Our study aimed therefore at assessing the risk of winter nitrate leaching during the first growth years of *M. giganteus* in a wide range of agricultural conditions, combining soil samplings on 38 farmers' fields and the use of LIXIM.

Table 3. 1 : Characteristics of the farmers' field network

Planting year	Preceding crop	Soil type*	% clay**	% sand**	Maximum sampling depth (cm)	Number of fields
2009	Set-aside (grassland)	C	46	12	120	2
		CC	37	25	40	1
		A	24	37	40	1
		LC	32	14	120	1
		L	21	22	120	3
	Annual crop	C	48	8	120	4
		CC	34	4	70	1
		A	-	-	-	-
		LC	35	24	120	3
		L	31	12	120	3
2010	Set-aside (grassland)	C	42	11	120	1
		CC	47	12	80	1
		A	14	60	110	1
		LC	34	15	120	2
		L	25	18	120	4
	Annual crop	C	51	11	120	3
		CC	30	31	50	1
		A	28	28	65	2
		LC	-	-	-	-
		L	27	18	120	2

* C: clay soil; CC: calcareous clayey soil; A: alluvial soil; LC: loamy clay soil; L: hydromorphic loamy soil.

** Mean value in the 0-120 cm layer.

2. Materials and methods

2.1. Description of the farmers' field network

We investigated a set of 38 farmers' fields located in Burgundy (Centre-East France) in a 3000 km^2 area ranging from 46°54' to 47°37' N and from 4°22' to 5°46' E (**Table 3.1**). The field survey was carried out during two growing seasons and two winters: winter 2010-2011 (hereafter referred to as Period 1) and winter 2011-2012 (Period 2). 19 fields were planted with *M. giganteus* in spring 2009 and 17 fields in spring 2010, after two kinds of preceding crops: annual crops (wheat, corn or sunflower) and set-aside (meadows established for more than five years). The fields covered five soil types, depending on depth and texture.

Fields were planted mechanically with rhizomes at densities ranging from 1.53 to 2.51 rhizomes per m^2 (mean = 1.93 rhizomes m^{-2}). The crops were chemically protected against weeds during the year of establishment and in the second year, before the first regrowth. When necessary, fields were also weeded before the second regrowth. 33 of the 36 fields were unfertilized. The three remaining fields were fertilized with about 30 kg N ha^{-1} in March or April. Shoots were not harvested at the end of the establishment year but were crushed at the end of December. During the following years, fields were mechanically harvested in late March or early April.

2.2. Measurements

Soil mineral nitrogen (snM), *i.e.* soil nitrate (SN) and soil ammonium (SA), along with soil water content (SWC), were measured five times from 2010 to 2012 at the end of winter, after harvest (in March 2010, early April 2011 and late March 2012) and at the beginning of winter (in mid-November 2010 and 2011). Samplings were concentrated within a short time period: the delay between the first and the last sampled fields did not exceed nine days and averaged five days. Soil cores were collected down to 120 cm maximum with a hydraulic coring device (auger diameter = 2 cm). Each core was split into four layers (0-30, 30-60, 60-90, 90-120 cm). Composite soil samples were made by mixing 10 cores collected across the field. The samples were frozen until extraction and subsequent analysis. Nitrate and ammonium were extracted using a KCl solution (1 M) and analyzed by continuous flow colorimetry. A soil subsample was weighed and dried for 72 hours at 105°C and gravimetric water content was estimated by measuring the weight loss after drying.

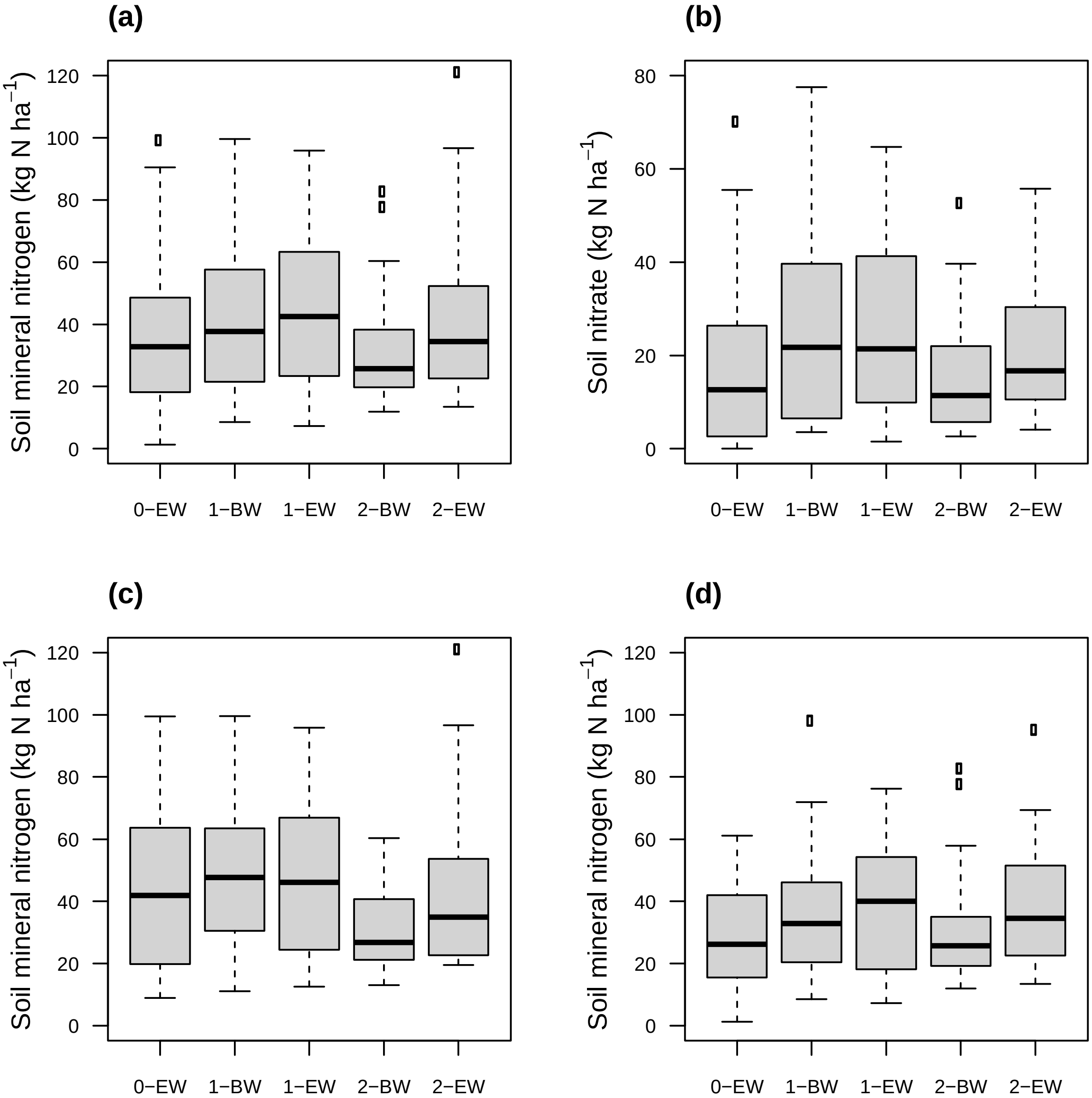

Figure 3. 1: a) Total soil mineral nitrogen (kg N ha^{-1}), b) Soil nitrate (kg N ha^{-1}), c) Total soil mineral nitrogen for fields which were set-aside before the plantation of *M. giganteus* (kg N ha^{-1}), d) Total soil mineral nitrogen for fields where arable crops were grown before the plantation of *M. giganteus* (kg N ha^{-1}).

0_EW: end of winter 2009-2010, 1_BW: beginning of winter 2010-2011, 1_EW: end of winter 2010-2011, 2_BW: beginning of winter 2011-2012, 2_EW: end of winter 2011-2012

On 20 of the fields, shoot density was measured at the end of the growing season on two 25 m^2 plots including six *M. giganteus* rows. These plots were randomly sited but precautions were taken to avoid field borders and extreme field areas that were not representative for the field.

2.3. LIXIM model

LIXIM (Mary *et al.* 1999) simulates both water and nitrate fluxes in soils and allows calculation of nitrogen mineralization and leaching in bare soils, assuming that these are the dominant processes affecting nitrogen. The model has been successfully assessed in various field experiments with bare soils(Justes *et al.* 1999; Mary *et al.* 1999). Since *M. giganteus* does not take up nitrogen or transpire during winter, it can be likened to a bare soil during the period considered here (from late autumn to early spring). LIXIM is a layered, functional model with a daily time step. Input data are SWC, SN and SA measured in soil cores, standard meteorological data and simple soil characteristics: bulk density (Da), water content at field capacity (θ_{fc}) and water content at wilting point (θ_{wp}). Two parameters can be estimated by fitting the observed and simulated SWC and SN in each soil layer at the end of the time interval: the ratio of actual to potential evapotranspiration (k) and the potential rate of mineralization (Vp). In this study, we set k at 0.60, which is a common value for a bare soil (Mary *et al.*, 1999) and fitted Vp for each field.

2.4. Step 1: characterizing and explainingthe variability of soil mineral nitrogen across fields during the first growth year of M. giganteus

We focused our analysis on the soil mineral nitrogen measured at the beginning of winter (snM_{BW}) since it is a key variable to assess the risk of nitrate leaching during winter. The analysis of variance with a mixed model (R Development Core Team, 2008, version 2.14.2, package lme4) was used to study the effect of soil type and crop characteristics (age, preceding crop) on snM_{BW}. A mixed model was used with soil type (SOIL), crop age (AGE) and preceding crop (PREC) as fixed effects while field and year were defined as random effects:

$$snM_{BW} = \mu + \alpha_1 AGE + \alpha_2 PREC + \alpha_3 SOIL + \beta PREC{:}SOIL + \gamma_f + \gamma_y + \varepsilon$$

Where μ is the intercept; $\alpha_1, \alpha_2, \alpha_3, \beta$ are unknown parameters; γ_f and γ_y stand for the random effects associated with the field and year respectively and follow a normal distribution $\gamma_f = N(0, \sigma_f)$ and $\gamma_y = N(0, \sigma_y)$; ε is the error term, $\varepsilon = N(0, \sigma)$. Significance of the fixed effects was assessed and partial r^2, *i.e.* r^2 estimated including only the fixed effects, were computed.

For fields where shoot density was measured, a second analysis was carried out using shoot density instead of crop age.

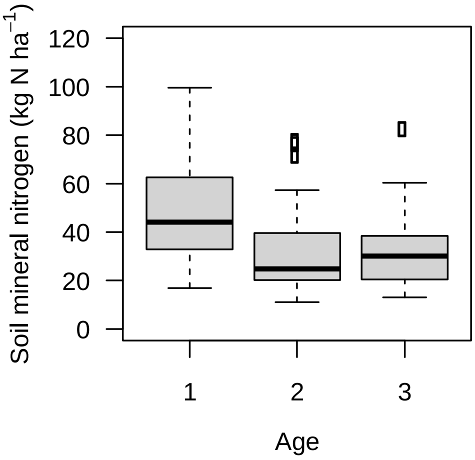

Figure 3. 2: Total soil mineral nitrogen (kg N ha^{-1}) measured at the beginning of winter as a function of crop age.

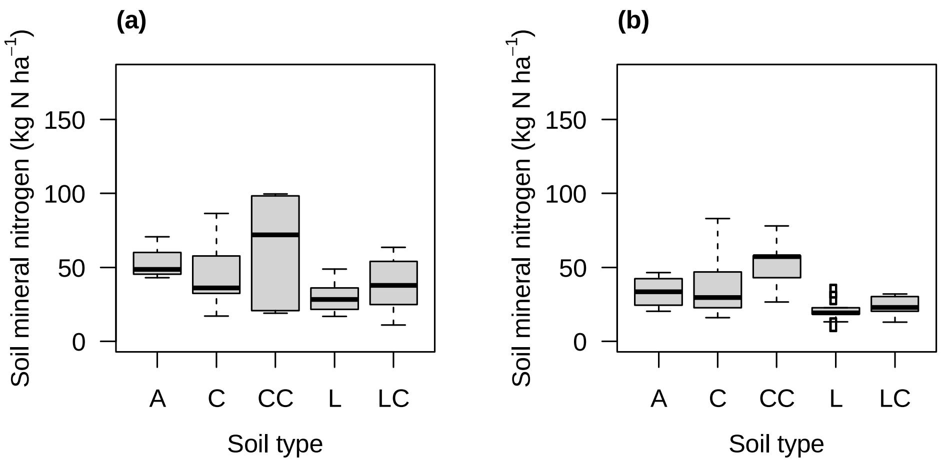

Figure 3. 3: Total soil mineral nitrogen measured at the beginning of winter a) 2010 and b) 2011 as a function of soil type.

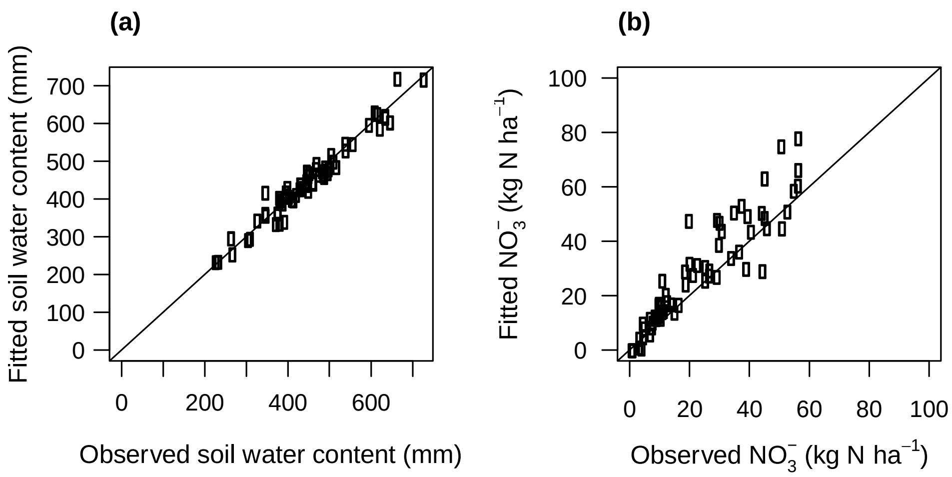

Figure 3.4: Comparison between observed and simulated values of: a) soil water content (mm) and b) soil nitrate (kg N ha-1) in late winter for both years.

Simulated values were obtained with LIXIM. The continuous lines are the 1:1 lines.

2.5. Step 2: nitrate leaching assessment with LIXIM

snM and SWC measured at the beginning of winter were used as initial values to run LIXIM. Weather data (daily rainfall, potential evapotranspiration and air temperature) were collected from two Meteo France weather stations (Ouges, 5°04’41’’ E – 47°15’38’’ N, and Chamblanc, 5°04’41’’ E – 47°15’38’’ N) and two stations set up for the study in Lucenay-le-Duc (4°29’53’’ E – 47°36’22’’ N) and Chissey sur Loue (5°44’12” E – 47°01’37’’ N). The data used for each field were taken from the closest weather station, which was always within 20 km. Input data for soil characteristics were estimated for each soil layer through direct measurements (soil moisture at field capacity θ_{fc}) or using pedotransfer functions (soil moisture at the wilting point θ_{wp} and bulk density *Da*). θ_{fc} was estimated as the mean value of SWC measured at the end of winter, assuming that soils were at field capacity at that period of time. We considered this assumption as acceptable since the mean SWC value was closed to the maximum SWC value observed during the study. θ_{wp} was calculated using information about soil texture and a pedotransfer function defined by Bruand *et al*. (2004). *Da* was estimated similarly and was then corrected by the proportion of pebbles. The depth below which drainage and leaching occurred was set as a function of crop age: 90 cm for one-year-old crops and 120 cm for two-year-old crops. This depth can be compared to the maximum rooting depth, which was measured on soil trenches in nine fields covering the range of soil types and crop ages of the on-farm network: we found that rooting depth did not exceed 75 cm for one-year old crops. In fields where the sampling soil depth was less than 120 cm due to mechanical constraints, the rooting depth was set as the mean sampling depth estimated from all the measurements on that field. The other model parameters, *i.e*. the maximum soil depth contributing to water evaporation Z_e and contributing to N mineralization *Zm* were determined using references from Mary *et al*. (1999).

We tested the ability of LIXIM to simulate the SWC and SN measured in late winter for all fields by comparing fitted values to observed values. We also computed the root mean square error and the mean relative error. A sensitivity analysis was made on the effect of varying the ratio of actual to potential evapotranspiration (*k*) on drained water, leached N and nitrate concentration in drained water, by varying *k*by±20% ($0.48 \leq k \leq 0.72$) and ±50% ($0.3 \leq k \leq 0.9$).

For each field and each winter, the amounts of drained water (DRAIN) and leached nitrate (QLN) and the mean concentration of nitrate in the drained water (CLN) were calculated using LIXIM. The influence of soil type and cropping system characteristics (crop age, preceding crop) was studied through analysis of variance using a mixed model with field and year as random effects (R Development Core Team, 2008, version 2.14.2, package lme4).

Table 3. 2: Sensitivity analysis of water drainage and N leaching to variation in *k* (*k*=0.60). Variations of drained water, N leached and [NO_3^-] as a function of *k* are shown.

k	DRAINED WATER (mm)	N LEACHED (kg N ha^{-1})	[$NO3^-$] (mg l^{-1})
0.30 (-50%)	21%	33%	23%
0.48 (-20%)	8%	7%	7%
0.72 (+20%)	-7%	-10%	-5%
0.90 (50%)	-13%	-20%	-9%

Table 3. 3: Factors influencing leached nitrate, drainage and nitrate concentration in drained water

	DRAINED WATER (mm)			N LEACHED (kg N ha^{-1})			[NO_3^-] (mg l^{-1})		
FIXED EFFECTS	p-value		partial r^2	p-value		partial r^2	p-value		partial r^2
Age	$7.7*10^{-8}$	***	0.36	$1.2*10^{-6}$	***	0.24	$1.3*10^{-6}$	***	0.37
Soil	$6.6*10^{-5}$	***	0.28	$6.6*10^{-8}$	***	0.45	$1.5*10^{-4}$	***	0.35
Preceding Crop	0.11		-	0.023	*	0.05	0.12		-
Preceding Crop : Soil	0.0026	**	0.20	$5.8*10^{-5}$	***	0.25	0.0050	**	0.24

3. Results

3.1. SMN measured at the beginning of winter

For all fields and all soil samplings, SMN averaged 39 kg N ha^{-1} (**Figure 3. 1a**). Between sampling dates, mean SMN varied little, from 31 kg N ha^{-1} (beginning of winter 2011) to 43 kg N ha^{-1} (end of winter 2011) on average. SMN varied greatly between fields, ranging from 9 to 100 kg N ha^{-1} at the beginning of winter 2010 and from 12 to 83 kg N ha^{-1} at the beginning of winter 2011. However at each date more than two thirds of the fields had SMN below 50 kg N ha^{-1}. On average, SMN consisted of half nitrate and half ammonium.

SMN measured at the beginning of winter (SMN_{BW}) is an indicator of nitrate leaching risk, and was strongly dependent on soil type (p-value = $1.2*10^{-4}$, partial r^2 = 0.45). It was also significantly linked to crop age (p-value = 0.0043, partial r^2 = 0.14), and weakly to preceding crop (p-value = 0.071, partial r^2 = 0.06) and the interaction between soil type and preceding crop (p-value = 0.062, partial r^2 = 0.16). In both years, calcareous clayey soils (CC) and alluvial soils (A) had the highest SMN_{BW} (on average more than 40 kg N ha^{-1}) while clay soils (C), loamy clay soils (LC) and hydromorphic loamy soils (L) had SMN_{BW} values ranging from 10 to 60 kg N ha^{-1} (**Figure 3.2**). L soils had the lowest soil mineral N contents at the beginning of winter. On the first two sampling dates (end of winter 2010 and beginning of winter 2011), fields that were set aside before the planting of *M. giganteus* tended to have higher SMN but this effect disappeared at the following samplings (**Figure 3. 1c and d**). SMN decreased when crop age increased, particularly between the first and the second growth year. The decrease was more variable between the second and the third growth year (**Figure 3. 3**). In the twenty fields where shoot density was measured, SMN_{BW} was negatively correlated with shoot density (p-value = 0.035, partial r^2 = 0.06).

3.2. Assessment of the ability of LIXIM to simulate soil water content (SWC) and soil nitrate (SN) in late winter

LIXIM was able to reproduce the soil water content (SWC) and the soil nitrate content (SN) measured in late winter (**Figure 3. 4**). The root mean square error was 35 mm for SWC and 8.3 kg N ha^{-1} for SN. The goodness of fit as a function of soil depth was good for SWC (data not shown). For SN, the goodness of fit was good for the 0-30 cm (mean observed SN = 9.9 kg N ha^{-1}, mean simulated SN = 9.3 kg N ha^{-1}) and the 30-60 cm layers (mean observed SN = 7.0 kg N ha^{-1}, mean simulated SN = 7.4 kg N ha^{-1}) and decreased for the deeper layers, 60-90 cm and 90-120 cm. This result was consistent with the modelling approach since simulated SN was highly dependent on the fitted potential rate of N mineralization, while the maximum soil

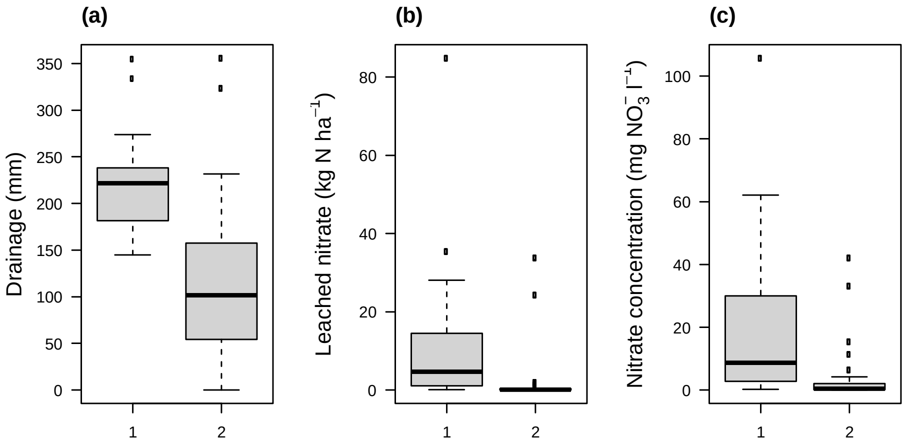

Figure 3. 5: LIXIM simulation results: a) drained water, b) leached nitrate and c) mean nitrate concentration in drained water

Period 1: winter 2010-2011; period 2: winter 2011-2012.

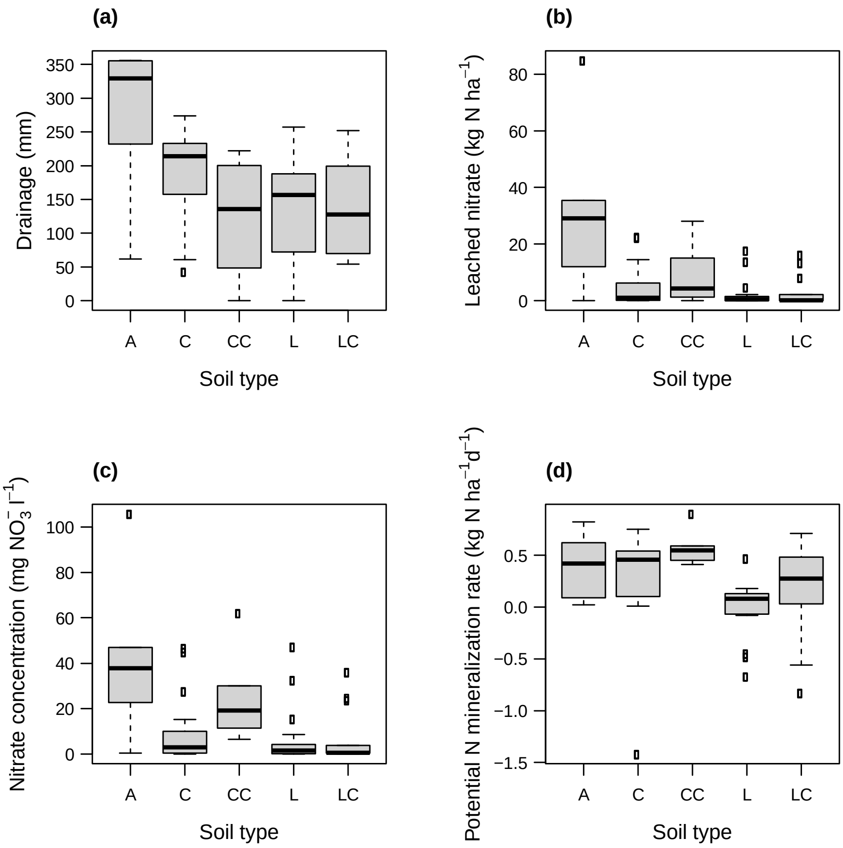

Figure 3. 4: LIXIM simulation results as a function of soil type: a) drained water; b) leached nitrate; c) mean nitrate concentration in drained water; d) potential N mineralization rate.

A: alluvial soil; C: clay soil; CC: calcareous clayey soil; L: loamy soil; LC: hydromorphic loamy soil.

depth contributing to N mineralization did not exceed 36 cm. SN tended to be over-estimated in the 60-90 (mean observed SN = 3.0 kg N ha^{-1}, mean simulated SN = 5.5 kg N ha^{-1}) and 90-120 cm layers (mean observed SN = 1.1 kg N ha^{-1}, mean simulated SN = 1.9 kg N ha^{-1}).

The analysis of sensitivity to *k* (the ratio of actual to potential evapotranspiration) showed that it had little influence (**Table 3. 2**). The amounts of drained water and leached N and the mean nitrate concentration decreased when *k* increased and vice-versa. When *k* decreased by 20%, drainage, leached N and nitrate concentration increased by 8%, 7% and 7% respectively. The biggest variation in these three output variables was obtained for a 50% decrease in *k*: drained water and nitrate concentration increased by about 22% and leached N increased by 33%. However this low value of *k* (0.30) is unlikely. We concluded that the nitrate concentrations simulated by the model were not very dependent on model parameterization and can be treated with confidence.

3.3. Water drainage

The amount of water drained below the maximum sampling depth was variable between years (**Figure 3. 5**). The mean value was 216 mm during the first winter 2010-2011 and 115 mm during the second winter 2011-2012. This is mainly due to the weather, since the first winter was wetter than the second (for instance 295 mm versus 257 mm at the Ouges weather station, compared to 263 mm for the long term average estimated over the past twenty years). Between-field variability of drainage was high during winter 2010-2011 (range: 145-355 mm, sd = 48). Only two fields had drainage above 300 mm. They had A soils and the high drainage was due to the high proportion of sand in these soils. Drainage was even more variable during the second winter 2011-2012 (range: 0-356 mm, sd = 83). Four fields stood out: the highest values, above 300 mm, were found in the two previously-mentioned fields; two fields had no drainage. Drainage fluctuated around 50 mm in eight fields.

Analysis of variance, with year as a random effect, showed that drained water was influenced by soil type, crop age and the interaction between soil type and preceding crop (**Table 3. 3**). Drainage decreased with older crops, which can be related to an increase in crop transpiration due to the higher biomass produced when crop age increased.

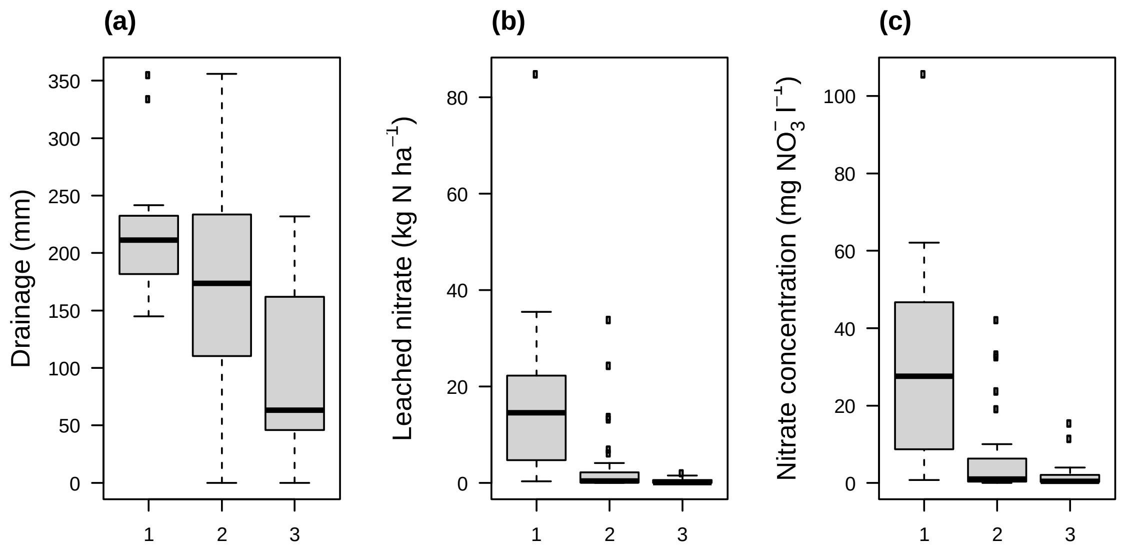

Figure 3. 7: LIXIM simulation results as a function of crop age: a) drained water (mm), b) leached nitrate (kg N ha^{-1}) and c) mean nitrate concentration in drained water (mg NO_3^- l^{-1}).

3.4. Nitrate leaching

N leaching varied greatly between sites and years (**Figure 3. 5**). During the first winter, the amount of leached N averaged 11 kg N ha^{-1}, but ranged between 0.1 and 85 kg N ha^{-1}; 80% of the fields had N leaching of less than 20 kg N ha^{-1}. During the second winter, the average amount of leached N was much lower (average 2 kg N ha^{-1}); 95% of the fields lost less than 5 kg N ha^{-1}. The amount of leached N was found to be influenced by weather, soil type (**Table 3. 3; Figure 3. 6**) and crop age (**Table 3. 3; Figure 3. 7**). Two soil types exhibited higher nitrate leaching: A soils and, to a lesser extent, CC soils. They represent the shallowest soils and, according to the model outputs, should have the greatest potential mineralisation rate (**Figure 3. 6**). Leached N decreased when crop age increased (**Figure 3. 7**). The lower rainfall observed during the second winter 2011-2012 influenced the decrease in leached N. However, variance analysis with year as a random effect demonstrated the significant effect of age (**Table 3. 3**). Unlike drainage, the preceding crop had a significant effect on N leaching, in addition to soil type and the interaction between soil type and preceding crop (**Table 3. 3**).

3.5. Nitrate concentration of drained water

Nitrate concentration in drained water averaged 20 mg NO_3^- l^{-1} during the first winter and ranged from 0.2 to 116 mg NO_3^- l^{-1} (sd = 24 mg NO_3^- l^{-1}) (**Figure 3. 5**). The concentrations decreased during the second winter, ranging from 0 to 42 mg NO_3^- l^{-1} with an average of 4 mg NO_3^- l^{-1} (sd = 10 mg NO_3^- l^{-1}). They were all below the European threshold of 50 mg NO_3^- l^{-1}. 15% of the fields were close to or exceeded the threshold during the previous winter. Nitrate concentration was significantly influenced by soil type and an interaction between soil type and preceding crop (**Table 3. 3**). It was also markedly dependent on crop age (partial r^2 = 0.37): the concentration was much lower in older crops (two or three years old) than in first year crops (**Figure 3. 7**).

4. Discussion

The aim of this paper was to assess nitrate leaching during the first establishment years of *M. giganteus*. Our study was based both on a farmers' field network to measure soil mineral nitrogen and soil water content and on a model to simulate nitrate leaching during winter from the measured data before and after winter. Our approach relied on a large number of actual farmed sites rather than on a limited number of experimental sites with numerous replicate measurements, our aim being to give an account of the between-field variability, which is scarce in the literature on *M. giganteus*. Direct measurements of water and nitrate fluxes through lysimeters or drained perimeters could obviously not be used in our situation. Ceramic cups would have provided information on nitrate concentration but not on water fluxes and could not have been installed on all the fields. Combining soil core samplings and the use of a model to convert measurements into fluxes was therefore a suitable approach which allowed us to quantify not only the amount of N leached but also the nitrate concentration of the drained water. The amount of N leached is an important criterion because it is both a potential pollutant and a valuable resource. However, in the context of the EU limit for drinking water of 50 mg l^{-1}, it is also relevant to consider nitrate concentration. As mentioned by Goulding *et al.* (2000), although it is likely that nitrate in drained water leaving a field will be diluted or denitrified 'between drain and stream or soil and aquifer', it is appropriate to take the EU limit as a target.

Nitrate leaching assessed in our study was on average very low. It was much greater during the first winter 2010-2011 (average =11; min=0.1, max= 85 kg N ha^{-1}) than during the second, 2011-2012 (average = 2; min=0; max= 34 kg N ha^{-1}). The reduction between the two years could be mainly attributed to the age of the crop but to also to the effect of weather. The nitrate concentration calculated in drained water averaged 12 mg l^{-1} in our study but varied from 0 to 106 mg l^{-1} over sites and years. Christian *et al.* (2008) found that the 10 year-mean N winter losses increased from 22 kg N ha^{-1}in unfertilized crops to 63 kg N ha^{-1}in crops receiving 120 kg fertilizer-N ha^{-1}. These average values are strongly influenced by the peak value of 154 kg N ha^{-1} measured during the first winter after establishment, which was attributed to previous agricultural practices and heavy winter drainage (Christian & Riche, 1998). The results of McIsaac *et al.* (2010) are much more comparable to ours since they measured annual nitrate losses (from spring to spring) averaging 3 kg N ha^{-1} y^{-1}. Christian and Riche (1998) observed nitrate concentrations averaging 12 mg l^{-1} during the first three growth years, which is very close to our findings, while Beale and Long (1997) measured a slightly higher concentration averaging 18 mg l^{-1}. On a watershed scale, Ng *et al.* (2010) used a *M. giganteus* crop model combined with a hydrological model to show that introducing the crop into a watershed can decrease the nitrate load. When 10, 25 or 50% of the farmed area was converted to *M. giganteus* (with 90 kg N ha^{-1}as fertilizer) instead of a corn/soybean rotation (with 190 kg N ha^{-1} applied on corn), nitrate load decreased by 6.5, 16.5 and 29.5% respectively. In contrast, using the same model as Ng *et al.* (2010), Wu & Liu (2012) found that converting 10% of cornfields to *M. giganteus* in a watershed did not affect the nitrate load while converting all the native grassland of the same watershed to *M. giganteus* increased the nitrate load by 5%.

All these results are clearly lower than the average losses usually measured for conventionally managed arable crops. For instance, Beaudoin *et al.* (2005) used LIXIM in northern France on cropping sequences based on winter rapeseed, winter cereals, spring pea and sugar beet. They found that a mean amount of leached nitrate of 27 kg N ha^{-1} (with a range of 16 to 50 kg N ha^{-1} according to the soil, and 11 to 42 kg N ha^{-1} according to the crop). Those losses lead to a mean nitrate concentration of 49 mg l^{-1} with a range of 31 to 92 mg l^{-1} according to the soil type and of 32 to 80 mg l^{-1} according to the crop. Constantin *et al.* (2010) found that conventional farming systems in northern France monitored over 13-17 years lead to a mean nitrate concentration varying from 53 to 109 mg l^{-1}. Likewise, on 256 fields located in Germany, Nieder *et al.* (1995)estimated with a model that leached N ranged from 16 kg N ha^{-1} for sugar beet to 88 kg N ha^{-1} for maize, and 20-40 kg N ha^{-1}for cereals. Stopes *et al.* (2002), comparing organic and conventional farming, found leaching losses of 46 kg N ha^{-1} for an organic clover-based ley-arable system, 58 kg N ha^{-1} for a conventional long-term arable system and 57 kg N ha^{-1} for conventional long-term grass. On the long-term Broadbalk experiment, Rothamsted, UK, mean amounts of N leached from continuous winter wheat fertilized with an optimum amount of 150-200 kg N ha^{-1} were about 30 kg N ha^{-1} but ranged from 10 to 60 kg N ha^{-1} under the influence of the weather (Goulding *et al.*, 2000).

Basically, low nitrate losses may be due to low soil nitrogen content at the beginning of winter and to low drainage during winter. Nitrate concentrations are reduced by low soil nitrogen content but are also reduced by high drainage due to a dilution effect. In our study, drainage averaged 166 mm but differed severely between period 1 where it was about 216 mm and period 2 with an average of 115 mm. It was also much more variable during period 2 (0 to 356 mm), than during period 1 (145 to 355 mm). Beaudoin *et al.* (2005) estimated with LIXIM higher drainage values that averaged 231 mm (219 to 263 mm according to soil type) while Constantin *et al.* (2010)measured with a lysimeter drainage of about 200 mm with catch crop (94 to 563 mm according to the site) and 215 without catch crop (120 to 593 mm). Goulding *et al.* (2000) observed on the Broadbalk long-term experiment a 10 year-mean of 245 mm (range: 111 to 474 mm). Drainage as estimated in our study was thus rather low. Nevertheless, besides drainage, nitrate losses estimated in our study can also be related to the small amount of soil mineral nitrogen measured (SMN) at the beginning of winter. Total soil mineral nitrogen (SMN) that we measured in late autumn averaged 42 kg N ha^{-1} for the first period (winter 2010-2011) and 31 kg N ha^{-1} for the second one (winter 2011-2012). These average values were lower to those found by Beaudoin *et al.* (2005) in northern France where total SMN for different arable crops averaged 55 kg N ha^{-1}. Furthermore, SMN in our study consisted of half nitrates and half ammonium, whereas SMN contained only 17% of ammonium in theirs.

The low average values observed for SMN at the beginning of winter were associated with high variability: from 9 to 100 kg N ha^{-1} for the first period and 12 to 83 kg N ha^{-1} for the second. The same high variability was observed for leached nitrate (from 0 to 85 kg N ha^{-1}) and nitrate concentration (from 0 to 106 mg l^{-1}). Values reported in the literature are commonly variable but to a smaller extent. For instance, Beaudoin *et al.* (2005) observed SMN ranging from 40 to 64 kg N ha^{-1} according to the soil type and from 40 to 95 kg N ha^{-1} according to the crop, 95 kg N ha^{-1} being observed after a pea crop. Likewise, Nieder *et al.* (1995) simulated N leaching ranging from 16 to 88 kg N ha^{-1} according to the crop. The presence of very low SMN in our study could be due to the studied crop and to the soils included in the on-farm design. *M. giganteus* was mostly unfertilized whereas it might still absorb nitrogen until late in autumn through an extensive rooting system (Neukirchen *et al.*, 1999; Monti & Zatta, 2009). Moreover, as it is a perennial crop, it is likely that the lack of cultivation in the second and third years reduced mineralization of soil organic matter, as suggested by Christian and Riche (1998). Besides, our on-farm design included some with very loamy hydromorphic soils where N mineralization is presumably low. On the other hand, high SMN was found on deep clay soils and calcareous clayey soils deeper than 80 cm, where mineralization rates were higher. The on-farm design also included fields where the crop failed to establish, resulting in very low shoot densities of less than 15 shoots m^{-2}, compared with an average of 35 shoots m^{-2} and a maximum of 60 shoots m^{-2} on the densest crops. Those fields with low shoot densities also had higher SMN, which may have been due to low nutrient uptake due to the poor growth of the crop. Smith *et al.* (2013) highlighted as well that establishment problems in *M. giganteus* caused a lag in nitrate leaching decrease.

Our results show a strong influence of soil type. Besides the effect of the mineralization rate on SMN mentioned above, soil type also influenced the amount of drained water: the soil with the highest sand contents had the highest amount of drained water. As these soils also exhibited the highest mean amount of leached N, they had the highest mean nitrate concentration. The influence of soil type was similar to the observations made by Nieder *et al.*(1995), Boniface (1996), Simmelsgaard (1998) and Beaudoin *et al.* (2005) on annual crops: deep clayey or loamy soils experience lower nitrate leaching than shallow soils, in particular when the latter have a high sand content. Nieder *et al.* (1995) estimated in Germany N leaching averaging 16 kg N ha^{-1} for coarse soils (*i.e.* sandy soils) and 63 kg N ha^{-1} for fine-textured soils (*i.e.* silty, loamy and clay soils). The relative differences between soils were said to be smaller for concentration than for leaching, which may result from dilution by water in shallow and/or sandy soils (Simmelsgaard, 1998; Beaudoin *et al.*, 2005). We observed that phenomenon, but the difference in nitrate concentrations between the shallowest soils of our study (CC and A) and the others was still significant. It is interesting to note that the soils with the lowest N leaching, *i.e.* deep clayey or loamy soils, were also the ones with the highest shoot densities, *i.e.* the ones where we can expect the highest yields.

Besides soil type, we also noticed an effect of crop age, which can be related to the crop development: during the first year of growth, shoot density and plant height remain low, leading to a smaller nutrient and water absorption. Christian and Riche (1998) also found that N losses decreased when crop age increased. During the first winter following planting of *M. giganteus* without fertilization, they observed losses of 154 kg N ha^{-1}. That amount decreased to 8 and 3 kg N ha^{-1} during the two following winters, which is similar to the dynamic observed in our study. However, in our study, the amount of nitrate leached during the winter after establishment averaged only 17 kg N ha^{-1} (min=0.1 kg N ha^{-1}, max=85 kg N ha^{-1}). Yet, Christian and Riche (1998) mentioned that previous agricultural practices (*i.e.* long-term grass four years earlier and incorporation of bean residues) may have induced a high rate of N mineralization. Besides, drainage amounted to 478 mm during the first winter of their experiment, while it averaged 200 mm in our study. In the following winters drainage was closer to what we estimated: 262 and 150 mm against an average of 166 mm in our study. Christian and Riche (1998) observed a mean nitrate concentration of 32 mg l^{-1} for the first winter and of 3 and 2 mg l^{-1} for the following two. Due to the difference in drainage, the mean nitrate concentration we estimated for the first winter was very similar to theirs (31.3 mg l^{-1}). In the winters after the second and third years of growth these concentrations were about 7 and 3 mg l^{-1} respectively, which is also similar to their values.

5. Conclusion

Combining nitrate and water content measurements on 36 fields with the use of the LIXIM model to estimate nitrate and water fluxes, our study confirmed that growing *M. giganteus* results in low N leaching during the first years of growth, strengthening the idea that the crop is associated with a low risk of groundwater pollution by nitrates. Estimated mean nitrate concentration averaged 12 mg l^{-1}, far below the European limit of 50 mg l^{-1}.We also confirmed that the highest risk is in the first year of growth, when crop development is at its lowest.

Although we showed that nitrate leaching was low on average, we also found that it was very variable. The variability was not only associated with crop age but also with soil type and crop development. Unlike earlier experimental studies on M. giganteus, our on-farm design included a wide range of soil types and growing conditions. Deep loamy or clayey soils exhibited the least N leaching. Conversely, we found that the risk of N leaching was the highest in two situations: (i) in fields with shallow and/or sandy soils and (ii) when crop establishment fails. As fields with shallow and/or sandy soils have low available soil water, they have also a higher probability of establishment failure.

Except for those risky situations, our study confirmed that regarding nitrate losses, M. giganteus has a better environmental profile than annual crops. Available comparisons with other perennial candidate bioenergy crops such as switchgrass or short rotation coppice suggest that those crops present the same advantage in terms of N leaching as M. giganteus when they are unfertilized (Makeschin, 1994; Aronsson et al., 2000; Aronsson & Bergstrom, 2001; McIsaac et al., 2010). However the nutrient requirements of those crops are commonly said to be higher than those of M. giganteus (Lewandowski et al., 2003; Powlson et al., 2005; Heaton et al., 2010). Furthermore, recent findings suggest that N2O emissions from M. giganteus are also low (Drewer et al. 2012; Gauder et al. 2012), confirming that the crop is associated with low N losses into the environment, which strengthens its potential as a bioenergy crop. Besides, Gopalakrishnan et al. (2012) suggested that bioenergy crops such as M. giganteus could also be grown in buffer strips adjacent to current agricultural crops. With such a spatial configuration, the bioenergy crops could reuse nutrients present in runoff and leachate from the conventional row-crops, thus allowing energy production while providing environmental services.

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Chapitre 4.

Evolution à long-terme des rendements de *Miscanthus* x *giganteus*

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Modelling long-term yield trends of *Miscanthus* x *giganteus* using experimental data from across Europe

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Abstract

Miscanthus x *giganteus* is a perennial grass that is considered to have a high feedstock potential for bioenergy production. Assessment of that potential is however highly related to the crop yields and to their change through the crop lifetime, which is expected to be longer than 20 years. *M. giganteus* is known to have an establishment phase during which annual yields increased as a function of crop age, followed by a ceiling phase, the duration of which is unknown. We built a database including 16 European long-term experiments (i) to describe the yield evolution during the establishment and the ceiling phases, (ii) to determine whether *M. giganteus* ceiling phase is followed by a decline phase where yields decrease across years. Data were analysed through comparisons between a set of statistical growth models. The model that best fitted the experimental data included a decline phase. The decline intensity and the value of several other model parameters, such as the maximum yield reached during the ceiling phase or the duration of the establishment phase, were highly variable. The highest maximum yields were obtained in the experiments located in the Southern part of the studied area and the duration of the establishment phase was strongly related to the establishment method. Since energetic viability and profitability of *M. giganteus* hinge critically on yields, these results could be integrated in further assessment works.

Keywords

Miscanthus x *giganteus*; perennial crop; meta-analysis; yield trend; yield decline; bioenergy

1. Introduction

Miscanthus x *giganteus* is a perennial C4 rhizomatous energy crop originating from Southeast Asia (Lewandowski *et al.*, 2000). It is known for its high yield potential and low input requirement (Lewandowski *et al.*, 2000, 2003). *M. giganteus* has been studied as an energy crop since the mid-1980s, mostly in the European Union (Lewandowski *et al.*, 2003). According to (2000), the crop is characterised by a yield increase during an establishment phase, lasting three to five years, followed by a ceiling phase with stable yields. Miguez *et al.* (2008) quantified those two phases using a meta-analysis: they described the growth of *M. giganteus* over years with a logistic function and estimated that it takes between three to five years to attain mature yields. Once mature yields are reached, *M. giganteus* is expected to have a plantation lifetime of 20-25 years (Lewandowski *et al.*, 2000). However, Clifton-Brown *et al.* (2007), Christian *et al.* (2008) and Angelini *et al.* (2009) studied the evolution of *M. giganteus* yields for 16, 14 and 12 years respectively, and observed a third growth phase characterised by a yield decline beginning after 10, 11 and 3 years of growth respectively. Such a decline has already been reported for other perennial crops such as sugarcane (*Saccharum* spp.), a C4 tropical grass from the same tribe of the genus *Miscanthus (Andropogoneae)* (Hoy and Schneider, 1988; Keerthipala and Dharmawardene, 2000; Ferraro *et al.*, 2009). At the same time, *M. giganteus* ceiling yields varied between trials: Lewandowski *et al.* (2000), Heaton *et al.*(2004) and Miguez *et al.*(2008) reported yields ranging from less than 10 to more than 40 t of dry matter (DM) per hectare across Europe. The knowledge of *M. giganteus* yield and of its evolution over time is essential in estimating the economic and carbon mitigation potential of the crop. As *M. giganteus* incurs a high establishment cost (e.g. more than 3000 € per hectare in the UK; Lewandowski *et al.*, 2000), yields determine partly the crop profitability (Styles *et al.*, 2008). The greenhouse gas balance associated to the crop was also proved to be sensitive to yields (Styles and Jones, 2007; Hillier *et al.*, 2009; Eranki and Dale, 2011). However, assessment studies are mainly based on experimental yields measured during the first growth years or on models built on those yields (Styles & Jones, 2007, 2008; Styles *et al.*, 2008; Smeets *et al.*, 2009; Hillier *et al.*, 2009; Monti *et al.*, 2009b). Our study aimed therefore at characterizing the long-term yield evolution of *M. giganteus* to answer the following questions: do yields decline and when? What is the variability of the maximum yield values? How long does it take to reach the ceiling phase?

2. Material and methods

2.1. Data

Our work was based on a quantitative review of various types of data gathered from across Europe. A database containing 37 experimental units (EU) – defined as the combination of a location and of an experimental treatment over several years – was built by consulting peer-reviewed papers, grey literature and unpublished data from research and research-development European institutions identified as working on *M. giganteus* (**Annexe 2**). We focused on institutions located in the European Union where long-term trials were available, while research on biomass crop in the United States of America was during a long time focused on switchgrass (Lewandowski *et al.*, 2003; Heaton *et al.* 2010). Experimental units were included in the database if the trial duration was more than 12 years and if yields had been measured on average at least every two years.

The 37 experimental units spanned five countries and 16 sites representing different pedo-climatic conditions (**Figure 4. 1**): Denmark (site 1: 4 EU; site 2: 6 EU), United-Kingdom (site 3: 3 EU; site 4: 4 EU), Austria (sites 5 to 9, one EU per site), Germany (site 10: 5 EU; site 11: 3 EU; site 12 to14: one EU per site; site 15: 2 EU), Ireland (site 16: 1 EU). For the last site (Ireland), data were collected from the Figure 2 of Clifton-Brown *et al.* (2007) using the freeware Digitizer. Each EU is characterized by the pedo-climatic conditions (soil type, mean annual rainfall, and temperature), the duration of the experiment, the experimental treatment or the crop management, and the yield measurement method (**Annexe 2**). Pedo-climatic conditions are mainly representative of Northern Europe. Experiment duration ranged from 12 to 22 years. The establishment method (plantlets or rhizomes), the plantation density and the fertilization were precised for all experimental treatments. Chemical and/or mechanical weeding was applied on every EU during the establishment years as well as during the following years, though not every year. None of the site was irrigated. Yield evolution of *M. giganteus* of all sites and EU depending on plant age is presented in **Figure 4. 2**.

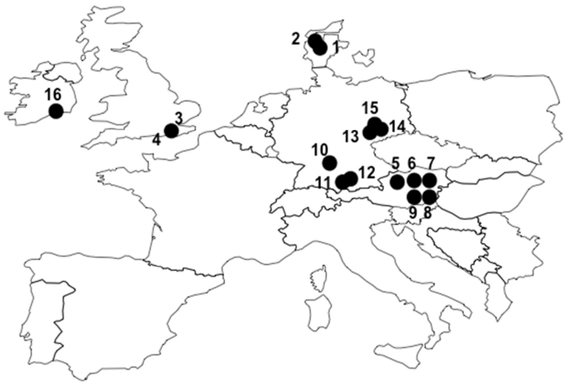

Figure 4. 1: Location of the experimental sites included in the *M. giganteus* long-term yield database (a site can include several experimental units, cf. Annexe 2).

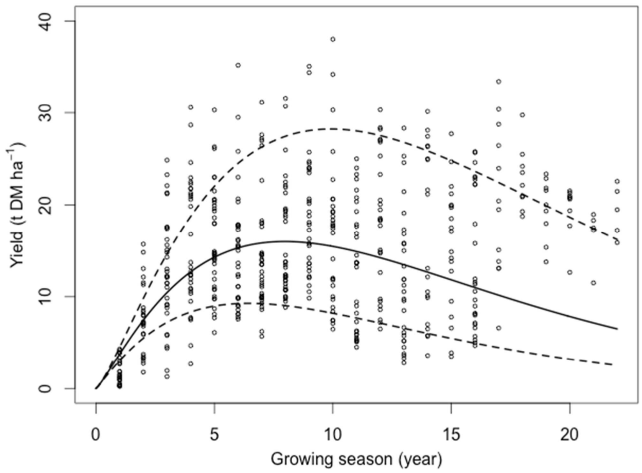

Figure 4. 2: Yield evolution of *M. giganteus* as a function of crop age.

Points represent the data, the solid line shows the mean prediction from model (4g), dashed lines represent the 2.5 and 97.5% percentiles describing the between site-year variability.

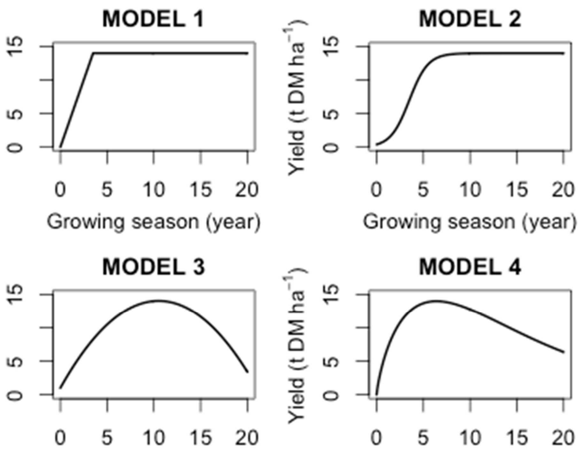

Figure 4. 3: Compared models for long-term yield trends.

2.2. Statistical models used to describe yield evolution

Five types of statistical growth models linking the yield (*Y*) and the growing season (*T*) were compared (**Figure 4. 3**):

- ‘Linear + plateau’ models based on a maximum yield (*Ymax*) and a threshold growing season (*Tmax*):

  If $T \geq Tmax$, $Y = Ymax$ (1)
  If $T < Tmax$, $Y = Ymax + S*(T-Tmax)$

- Logistic models:

  $Y = Ymax / (1 – \exp(\varphi_1 – T)/ \varphi_2$ (2)

  This model was used by (Miguez *et al.*, 2008) to describe *M. giganteus* growth over years.

- Quadratic models:

  $Y = \varphi_1 + \varphi_2*T + \varphi_3*T2$ (3)

- Exponential models:

  $Y = \varphi1 * T\varphi2* \exp(\varphi3*T)$ (4)

- ‘Linear + plateau + linear’ models based on a maximum yield (*Ymax*) and two threshold growing seasons (*T1* and *T2*):

  If $T1 < T < T2$, $Y = Ymax$ (5)
  If $T < T1$, $Y = Ymax + S1*(T – T1)$
  If $T > T2$, $Y = Ymax + S2*(T – T2)$

Models were chosen according to available knowledge on *M. giganteus* yield evolution in order to account for *M. giganteus* establishment phase and ‘plateau’ phase as described qualitatively by Lewandowski *et al.* (2000) and quantitatively by Miguez *et al.* (2008). Two families of models were compared regarding long-term yield evolution: (i) model (1) and (2) where yields remained constant in the long run and (ii) models (3), (4), and (5) which included a yield decline phase.

Due to the data structure (repeated measurements of yield over years in each EU), the models were defined as mixed-effect models, *i.e.* as models including one or several random parameters. For each type of model (linear+plateau, logistic, quadratic, exponential), several variants including 1, 2, or 3 random parameters were defined. For example, the model exponential including 3 random parameters was defined as follows:

$y_{ij} = \varphi_{1i} * t_{ij}^{\varphi 2i} * \exp(\varphi_{3i} * t_{ij}) - \varepsilon_{ij}$

$\varphi_i = (\varphi_{1i}, \varphi_{2i}, \varphi_{3i}) = (\beta_1, \beta_2, \beta_3) + (b_{1i}, b_{2i}, b_{3i}) = \beta + b_i$

$b \sim N(0,\Psi)$, $\varepsilon_{ij} \sim N(0,\sigma^2)$

Where (y_{ij}) stood for *M. giganteus* dry biomass, (t_{ij}) is the j^{th} growing season in the i^{th} experimental unit. The fixed effects β represented the mean values of the parameter φ_i over all experimental units, and the random effects b_i represented the deviations of φ_i from their mean value. The random effects were assumed to be independent for different EUs and to follow a normal distribution with a variance-covariance matrix Ψ. The within-group errors ε_{ij} were assumed to be independent for different *i* and *j*, and to be independent of the random effects. Models were fitted using the method described in Pinheiro and Bates (Pinheiro & Bates, 2000) implemented with the R software (R. Core, 2006) using the nlme (Pinheiro *et al.*, 2007) and lattice (Sarkar, 2007) packages.

Models were assessed by calculating the Akaike Information Criterion (AIC) and Schwartz Criterion (BIC) (Akaike, 1974; Burnham & Anderson, 2002). The best models are those with the lowest AIC and BIC. The distributions of the model residuals were checked for patterns, normality (with estimation of Skewness and Kurtosis) and autocorrelation.

Two sensitivity analyses were carried out to assess the robustness of the AIC and BIC-based model ranking. The first one was made at the EU level: each EU was removed from the data one by one and effects on the model ranking were noted. The second sensitivity analysis was made with a similar method but at the site level.

2.3. Characterization of yield trend and variability

The best model (i.e. the model with lowest AIC and BIC values) was used to estimate three characteristics of yield trends over years:

- the maximum yield *Ymax* reached across years (t DM ha^{-1});
- the growing season when the maximum yield *Ymax* was reached *Tmax* (year);
- the yield decrease rate *ΔY* (t DM ha^{-1} $year^{-1}$), calculated as follows:

$$\Delta Y = (Y(22) - Ymax) / (22 - Tmax) \quad (6)$$

where 22 was the last year simulated by the model and Y(22) the yield reached that year.

When *Ymax* and *Tmax* were not model parameters, they were computed using the model equation. For instance, for model (4):

$$Ymax = \varphi 1 * \left(\frac{-\varphi 2}{\varphi 3}\right)^{\varphi 2} * \exp(-\varphi 2) \quad (7)$$

$$Tmax = -\frac{\varphi 2}{\varphi 3} \quad (8)$$

$$\Delta Y = \frac{(22 * Tmax)^{\varphi 2} * \exp(22)}{\exp(Tmax)^{\varphi 3}} \quad (9)$$

The values of the three variables were estimated for each EU separately and the estimated values were related to several explanatory variables:

- groups of EUs based on *Ymax*, *Tmax* and *ΔY;* they were defined from a cluster analysis using the Euclidean distance measure and the ward agglomeration method;
- latitude and longitude;
- crop management techniques (planting method, planting density, fertilization regime).

Table 4. 1: Comparison of different yield evolution models for *M. giganteus*

MODEL	Parameter(s) defined with random effect	AIC	BIC
(1a)	None	3433.1	3504.0
(1b)	All	2914.8	2944.6
(1c)	Ymax	2922.3	2943.5
(1d)	S	3435.1	3456.4
(1e)	T	NC*	NC
(1f)	Ymax and S	2918.3	2943.8
(1g)	Ymax and T	2912.8	2938.3
(1h)	S et T	3437.1	3462.6
(1a)	None	3433.2	3450.2
(2b)	All	2884.2	2913.9
(2c)	Ymax	2881.1	2902.3
(2d)	φ1	3435.2	3456.4
(2e)	φ2	3435.2	3456.4
(2f)	Ymax and φ1	2882.6	2907.6
(2g)	Ymax and φ2	2883.1	2908.6
(2h)	φ1 and φ2	3437.2	3462.7
(3a)	None	3487.0	3504.0
(3b)	φ2	3128.5	3149.7
(4a)	None	3462.2	3479.2
(4b)	All	2854.4	2884.2
(4c)	φ1	2954.5	2975.8
(4d)	φ2	2947.1	2968.3
(4e)	φ3	2987.6	3008.9
(4f)	φ1 and φ2	2896.8	2922.3
(4g)	φ1 and φ3	2852.4	2877.9
(4h)	φ2 and φ3	2885.8	2911.3

* NC: not computed

Table 4. 2: Parameter estimates of the selected model (model 4g) – E stands for the parameter φi expectation and V(φi) for parameter φi variance

Parameter	Estimated value
E(φ1)	4.37
E(φ2)	1.21
E(φ3)	1.69
V(φ1)	2.85
V(φ2)	0
V(φ3)	1.46
σ^2	9.61

3. Results

3.1. Model selection

Models are compared in **Table 4. 1** with different combinations of random *vs*. fixed parameters. Some of the models were excluded when the convergence criteria of nlme were not satisfied. As all models (5) did not converge, they were not further included in the analysis.

Model (4g) with *φ1* and *φ3* defined as random parameters minimized both AIC and BIC. Model (3) led to intermediate AIC and BIC values. Models (1h), (2d), (2e) and (2g), which are characterized by a fixed *Ymax*, showed the highest AIC and BIC. The AIC and BIC were decreased when *Ymax* was defined as a random parameter – as for instance in models (1b), (1c), (1f), (1g), (2b), (2c), (2f) and (2g). This result was consistent with the high variability of maximum yields reported for the different EU. The AIC values of models (2b), (2c), (2f), and (4g) were similar, but model (4g) showed a lower BIC. Models (4b) and (4g) had very close AIC and BIC.

Figure 4. 4 shows the robustness of the AIC-based ranking of the tested models. Results obtained for BIC were similar (data not shown). Sensitivity analysis at the EU level showed that model ranking was stable with one exception: when EU 31 (GER – Freising [11]) was removed from the data, the logistic model (2f) became slightly better than model (4g) (**Figure 4. 4a**). At the site level, model classification was quite consistent as well, with two exceptions (**Figure 4. 4b**). When site 1 (*i.e*. DK – Hornum [EU 1 to 4]) was removed, the logistic model (2c) minimized with AIC with 2584.5, the model (4g) was ranked 5^{th} with AIC=2587.4. The original model ranking was more affected when site 11 (*i.e*. GER – Freising [EU 29 to 31]) was removed: models (2c) got the lowest AIC (2495.9) and model (4g) was ranked 8^{th} (2522.6). Logistic models – (2c), (2f) and (2g) – and linear+plateau models – (1b), (1f), (1g) – got a lower AIC than model (4g).

Model (4g) residuals presented no pattern and were consistent with the normality hypothesis (Skewness=0.1; Kurtosis=3.7). Model (4g) residuals were compared to those of the best model without decline phase (model 2c) (**Figure 4. 5**). Many of the model (2c) residuals were negative for high growing season values showing that model (2c) tended to overestimate yields for T > 15 years. **Figure 4. 5** shows that model (4g) was more in agreement with the observed yield data.

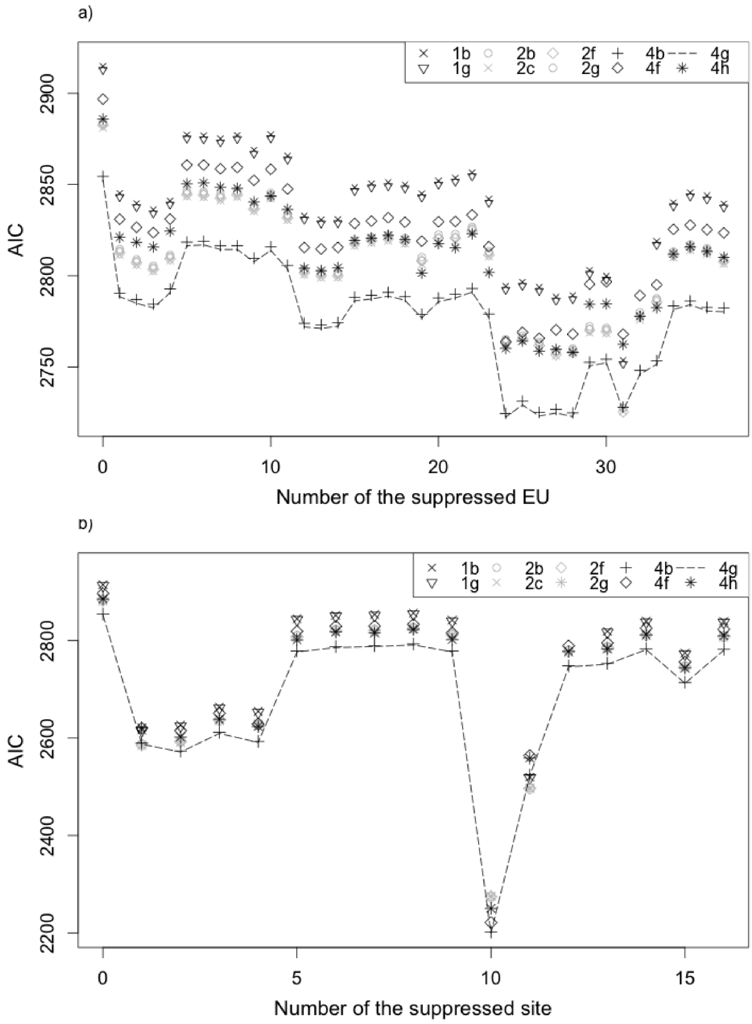

Figure 4. 4: Sensitivity analysis to the data, a) at the experimental unit level (EU) and b) at the site level.

For each suppressed EU or site (numbered on abscissa) is displayed the model classification result. Symbols stand for the AIC of the different models. Dashed lines stand for the AIC of model (4g).

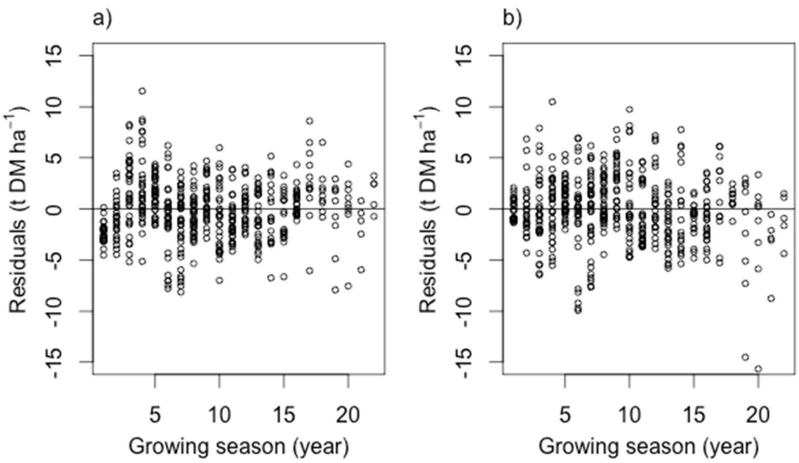

Figure 4. 5: Residual distributions for a) model (4g) and b) model (2c).

Based on these results, the exponential-based model (4g) was selected for further analysis. The mean yield response curve predicted by the model (4g) is displayed in **Figure 4. 2**. The 2.5 and 97.5% yield percentiles computed from the random parameter distributions (**Figure 4. 2**) showed high yield variations between experimental units. This result was confirmed by **Figure 4. 6** that revealed a strong variability of the fitted individual response curves between the different experimental units.

3.2. Yield trends and variability: analysis from model (4g)

Parameter estimates of model (4g) are shown in **Table 4. 2**. Long-term yield trends can be quite different across the experimental units (**Figure 4. 6**): some EUs such as EU 24 or 28 showed a significant yield decline whereas yields of other EUs such as EU 29 or 31 remained almost stable, even after 20 years of growth.

On average over EU, *Ymax* was equal to 16.8 t DM ha^{-1} y^{-1} (sd=6.86), *Tmax* was equal to 8.33 years (sd=1.95), and ΔY was equal to -0.647 t DM ha^{-1} y^{-1} (sd=0.243).

Cluster analysis (**Figure 4. 7**) split EUs into three groups of yield trends (**Figure 4. 8**):

- Group 1 includes experimental units 1 to 18 (i.e. location 1, 2, 3 and 4), 34 to 37 (i.e. location 14, 15, 16). It was characterized by maximum yields (*Ymax*) ranging between 8.4 and 16.3 t DM ha^{-1} y^{-1} with a median equal to 11.6 t DM ha-1 y^{-1}. These maximum yields were reached after 5.9 to 9.2 years with 7.2 years as a median.
  ΔY varied from -0.65to-0.36t DM ha^{-1} y^{-1}, with a median equal to -0.65 t DM ha^{-1} y^{-1}.

- Group 2 includes experimental units 19 to 23 (location 5, 6, 7, 8, 9), 30, 31 (from location 11) and 33 (location 13). *Ymax* were higher, ranging between 19.5 and 33.9 t DM ha^{-1} y^{-1} with a median of 23.0 t DM ha^{-1} y^{-1}. Maxima were reached after 6.7 to 9.8 years (median=6.7 years). Yields declined from -0.880 to -1.27 t DM ha^{-1} y^{-1} (median=-1.05 t DM ha^{-1} y^{-1}).

- Group 3 includes experimental units 24 to 28 (i.e. location 10), 29 (from location 11) and 32 (location 12). Maximum yields were high as well, ranging between 21.6 to 24.2 t DM ha^{-1} y^{-1} (median=23.6 t DM ha^{-1} y^{-1}). Maxima were however reached after 10.5 to 13.0 years (median=11.9 years) and ΔY were similar to those of group 1, ranging from -0.47 to -0.79 t DM ha^{-1} y^{-1} (median=-0.52 t DM ha^{-1} y^{-1}).

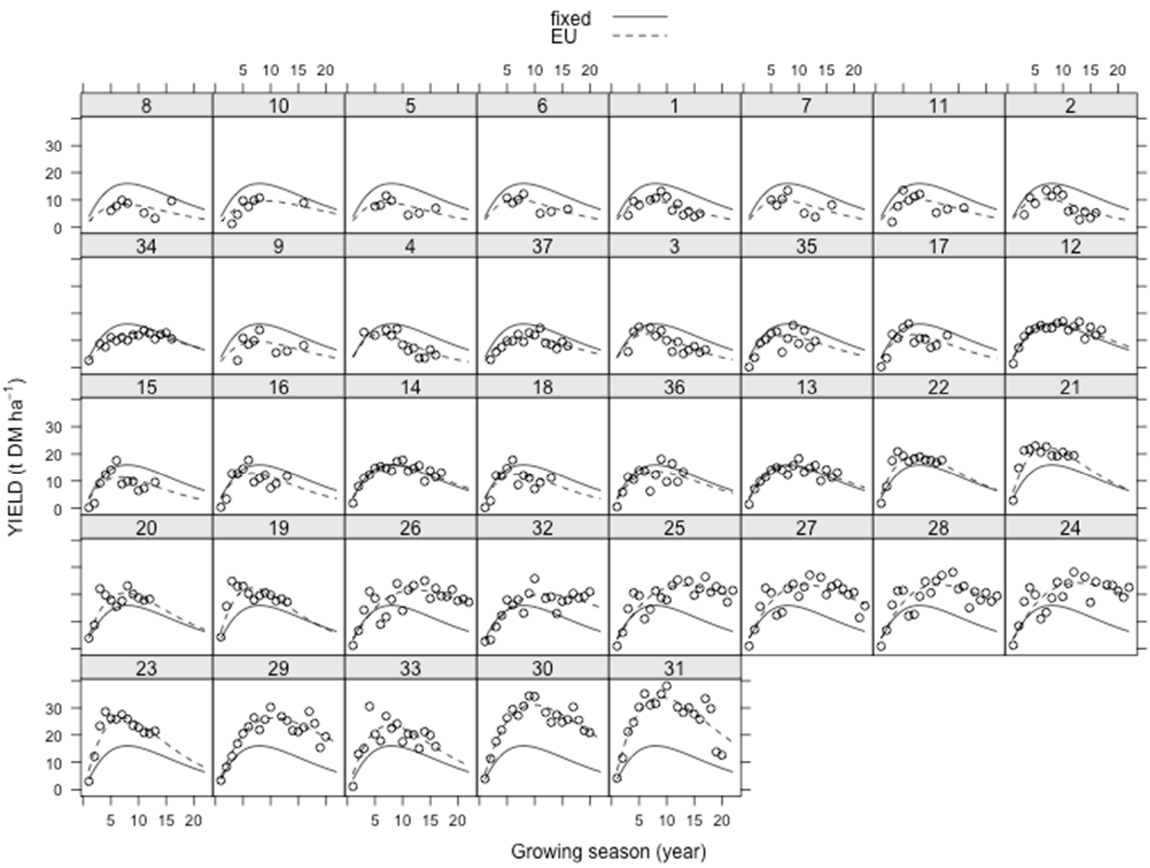

Figure 4. 6: Mean predictions (solid line) and experimental unit (EU) adjusted predictions (dashed line) of *M. giganteus* yield trends from the selected growth model (4g).

Ymax was strongly related to latitude (r^2=0.67) (**Figure 4. 9**): southern sites were those with the highest *Ymax*. It was correlated to none of the management techniques reported in the database. *Tmax* was strongly related to the planting mode (**Figure 4. 10**): EUs planted with rhizome needed on average more time to reach their maximum yields. It was not related to other management techniques. It also seemed to be determined by the site potential: the higher Y*max*, the higher *Tmax*. *ΔY*was found to be related to none of the variables studied here.

Experimental units classified in group 1 were located in the North. Two third of them were planted with micro-propagated plants. Except EU 33, group 2 includes EU located in the South and, for most of them, had crops established by micro-propagation. Group 3 includes EU located in the South planted with rhizomes.

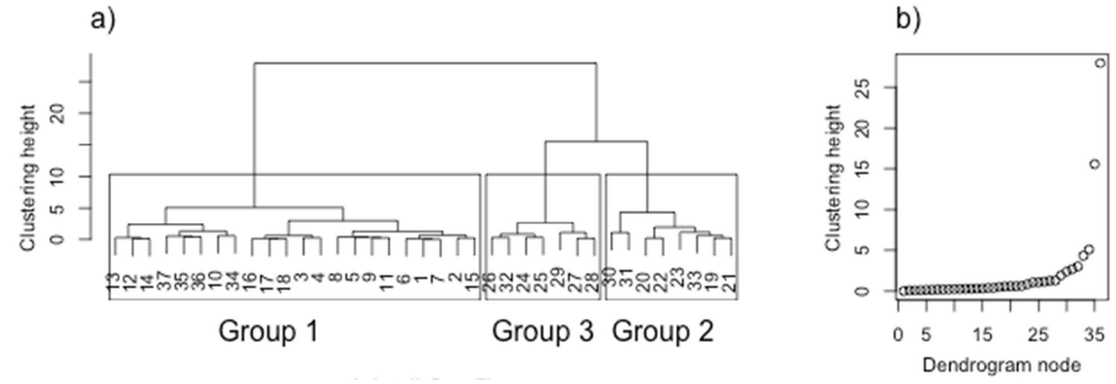

Figure 4. 7: a) Dendrogram of the experimental units and b) node distance graph as basis for grouping them into three groups.

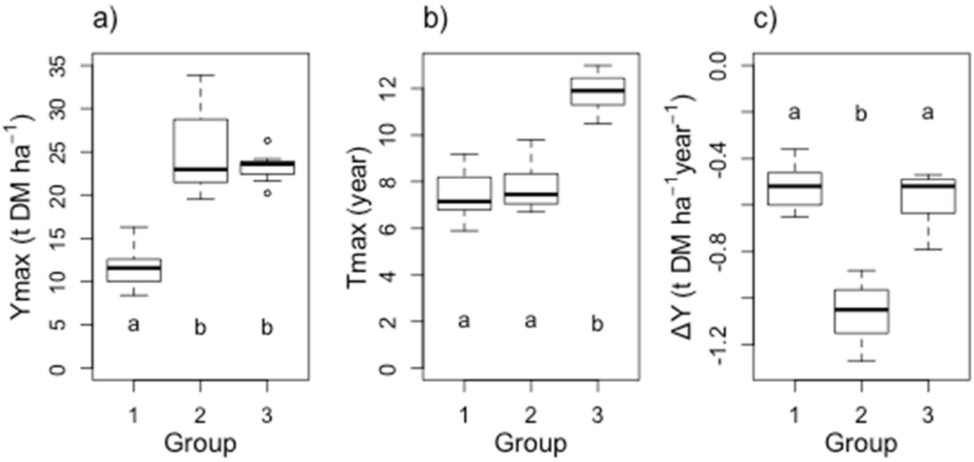

Figure 4. 8: Variation of a) Ymax, b) Tmax and c) ΔY according to the group of EUs. Different letters indicate that the group means are significantly different.

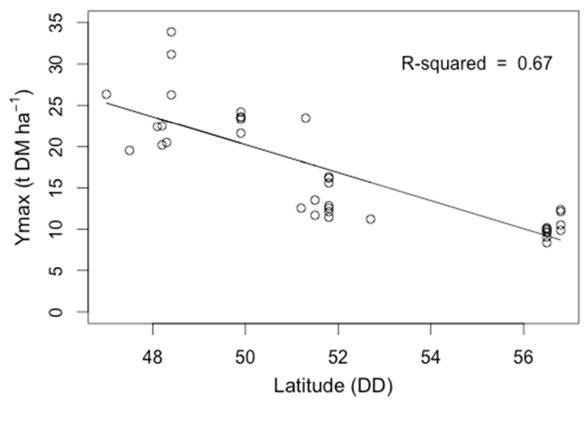

Figure 4. 9:Variation of Ymax as a function of latitude.

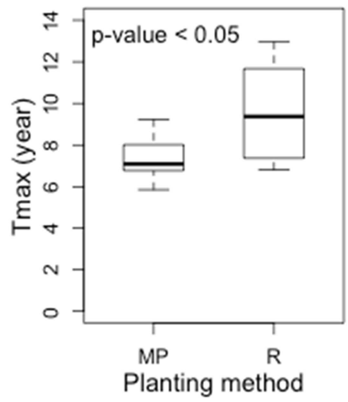

Figure 4. 10: Variation of Tmax as a function of the planting mode.

(MP : micro-propagation, R : rhizomes)

4. Discussion

4.1. Ceiling yields

Ymax averaged 16.8 t DM ha^{-1} y^{-1} but was characterized by a large variability (standard deviation: 6.86 t DM ha^{-1} y^{-1}). This is consistent with findings of (Miguez *et al.*, 2008) with average *Ymax* of 18.4 t DM ha^{-1} y^{-1} associated with a great variability too. (Heaton *et al.*, 2004) estimated higher *M. giganteus* mean yields (22.4 t DM ha^{-1} y^{-1}) but this remains in the same order of magnitude.

In this study *Ymax* appears to be determined by latitude with a strong gradient from North to South: countries at lower latitudes (Germany and Austria) achieved higher *Ymax* as a consequence of a longer growing season accompanied by higher temperatures. This outcome seems to confirm results presented by Miguez *et al.* (2008), whose database included Southern countries (Italy and Greece).

No correlations were found for *Ymax* and any management factors included in this study. Thus yield performances seemed to be more determined by environmental factors than by management. (Heaton *et al.*, 2004) also showed that *M. giganteus* yields were strongly influenced by water, barely influenced by nitrogen and not influenced by growing degree days at all. However, Miguez *et al.* (2008) found a relatively small effect of nitrogen on the maximum dry matter yield in the long-term, suggesting that the lack of N effect reported in many studies could be due to the short length of experimentation. In a review, Cadoux *et al.* (2012) indicated the low nutrient requirements of *M. giganteus* compared to other crops. Those low requirements are mainly due to high nutrient uptake and use efficiency, as well as nutrient cycling through translocation between the rhizome and aerial biomass and through leaf fall. Cadoux *et al.*, (2012) also mentioned that studies reporting no response to increasing nitrogen fertilization rate seemed to have benefited from high soil nitrogen levels. This might also have been the case with several experiments in our database. The lack of response to nitrogen could be also due to the presence of another limiting factor as on site 10, where the lack of water might have concealed any fertilization effect (Fritz and Formowitz, pers. comm.). Like Miguez *et al.* (2008), we did not find any effect of planting densities on *Ymax*. According to Lewandowski *et al.* (2000) and Jorgensen (1996), higher planting densities increase yields only during the first growing years.

Another part of the inter-location yield variability could be related to the differences in yield measurement method shown in Table 1. Yield measurement method for *M. giganteus* is indeed known to be protocol-sensitive (Brancourt-Hulmel, pers. comm.; Strullu, pers. comm.) but no precise comparisons are available.

4.2. Duration of the establishment phase

High planting densities are expected to reduce the length of the establishment phase. In our model, the duration of the establishment phase can be comprehended thanks to *Tmax*, which averaged 8.5 years. The full establishment of a *M. giganteus* stand is more commonly said to be ranging from three to five years (Lewandowski *et al.*, 2000; Miguez *et al.*, 2008, 2012). Since *Tmax* is the year where the absolute maximum yield is reached, it does not strictly represent the establishment phase. Assuming that the stand is fully established when 85% of Ymax is reached, we could estimate from our model that the establishment phase takes 4.7 years (ranging 3.3 to 7.3 years).

Tmax in our study was strongly influenced by the planting method: stands planted with micro-propagated plants establish faster than the ones planted with rhizomes. Lewandowski (1998) found that stands established from micro-propagules were characterized by a larger number of shoots per plant at the end of the first growing season. Shoots were on the other hand thinner and had less numerous and smaller leaves. Differences in shoot numbers and weight were still significant until the fourth growing season. Any influence on yield was on the contrary unclear during the first growing seasons and certainly did not exist in the long run. Clifton-Brown *et al.* (2007) observed higher shoot densities for micro-propagated plants from the first to the fifths growing season but plants were shorter. Yields were significantly different for the fifth and the sixth growing season but propagation method had no significant effect on yield over the six years. Effect on *Tmax* observed in our study may be explained by the higher shoot density observed for micro-propagated plants: establishment of a closed canopy may be faster and have more influence on yields than shoot weight. Lewandowski (1998) mentioned that micro-propagated stands are more sensitive to lodging, probably because of a smaller shoot diameter. Lodging can lead to yield losses and disturbs the nutrient translocation process. We could not include that factor in our analysis. However, lodging was also observed on stands planted with rhizomes, mostly during very snowy winters with the crop being repeatedly snowed under heavy-slushy snow (Fritz and Formowitz, pers. comm.) Micro-propagated plants are also characterized by a smaller overwintering rate after the first winter. Lewandowski (1998) showed that their rhizomes at the end of the first growing season were smaller than on plants established from rhizome pieces and had a different chemical composition. She assumed that a lack of reserve components in the rhizome resulted in increased susceptibility to frost. Such a phenomenon could not be observed in our study since new plants were planted when necessary after the first winter. Due to micro-propagation costs, commercial fields are nowadays planted with rhizomes, which although cheaper, is still expensive.

Miguez *et al.* (2008) found that *M. giganteus* reached higher yields faster when planting density was increased from 1 to 4 plants m^{-2}. This is in contrast to our results, where no influence of planting density on *Tmax* was observed. The range of planting densities included in our database (from 0.5 to 4 plants m^{-2}) is however large but unequally distributed within the database since lower and higher densities are tested only in Northern latitudes. Therefore, the effect of planting density could have been overcome by the effect of environmental factors.

Clifton-Brown *et al.*, (2001) as well as Zub and Brancourt-Hulmel (2010) reported that ceiling yields were reached faster in warmer countries. Nevertheless, we did not find any relationship between *Tmax* and latitude. Two hypotheses can be made. Firstly, potential yields as described by *Ymax*, may overcome the influence of latitude on *Tmax*: stands with high potential yields may need more time to reach *Ymax*, even if they are located in southern sites. Secondly, we might have seen this relationship if our database included southern locations such as Italy or Portugal.

Although we did not highlight any effect of management on *Ymax* or *Tmax*, it is interesting to notice that during the cluster analysis, all the units of the same site were allocated to the same group except for site 11. The three experimental units of site 11 (EU 29, 30 and 31) belonged either to group 3 for EU 29 and group 2 for EU 30 and 31. On that site, three nitrogen rates were tested: 0, 75 and 150 kg /ha. EU 29, where no nitrogen was applied, differed for *Ymax*, *Tmax* and ΔY at once: Ymax and Tmax were particularly smaller, suggesting a nitrogen effect on these two parameters at that particular site.

4.3. Yield decline

Our results indicated that *M. giganteus* yields followed a general tendency to decline after several years of growth. That tendency, already observed separately on several experimental locations (Clifton-Brown *et al.*, 2007; Christian *et al.*, 2008; Angelini *et al.*, 2009) was however quite variable between locations. In a recent report on a fourteen years experiment in Germany, Gauder *et al.* (2012b) highlighted a significant yield fluctuation between years but did not mention any decline. The long-term yield evolution variability observed in experiments was emphasized by the model selection carried out in our study: the mathematical form of the selected model, when used as a mixed effect model, allows the highest variability between experimental units.

Our analysis did not highlight any influence of management on this decline. Yet, the database used in this study did not allow us to take every management option separately into account. In particular, potassium and phosphorus fertilization was not included, whereas Cadoux *et al.* (2012) hypothesized that potassium may become a limiting factor for growth, according to *M. giganteus* potassium content in harvested aerial biomass. Even though our results did not show any influence of climatic conditions (summed up by latitude), we could expect a link between climate and yield decline. *M. giganteus* yield elaboration during a growth cycle is indeed divided into two parts (Himken *et al.*, 1997; Strullu *et al.*, 2011). From emergence in early spring to mid-summer, aboveground biomass increases slowly then strongly while nutrients are translocated from rhizomes to shoots. From mid-summer to mid-October, aboveground biomass increases slowly before decreasing until harvest at the end of the winter. Meanwhile, during this second phase, nutrients are translocated from the aerial parts to the rhizome (explaining, along with abscised leaves, above-ground biomass decrease). Early frosts in autumn may lead to insufficient translocation, reducing regrowth potential in the following spring (Clifton-Brown *et al.*, 2001). In the long run, we might hypothesize that early frosts may thus reduce the crop lifetime and further research should be carried out on this aspect. Early or late harvesting could also influence the crop decline: early harvests may disturb the nutrient translocation while late harvests may damage newly emerged shoots. Although EUs included in our database displayed some variability in harvest dates, no influence of the date was shown, probably because harvest dates varied both intra- and inter-EUs. Furthermore, soil compaction could also reduce crop yields and its perennity. Such a phenomenon is invoked to partly explain the yield decline observed for sugarcane successive ratoons (Keerthipala and Dharmawardene, 2000; Ferraro *et al.*, 2009). As for sugarcane, diseases and in particular belowground diseases may also be involved and be impacted by low winter temperatures or by waterlogged soils (Keerthipala and Dharmawardene, 2000; Ferraro *et al.*, 2009).

Beside management practices, yield decline could be related to the specific plant development. *M. giganteus* rhizomes grow from the inner part to the outer layer, building every year new rhizomes in a circle around the old ones. Thus in spring, new shoots emerge as a crown around the former shoots and the plant circumference increases. Over time the regrowth ability of the inner, older centre part is reduced leading to decreased biomass production. A rotary cultivation as done for rhizome harvest might then revitalize the stand, as observed in Denmark (Jorgensen, pers. comm.).

Finally, *Ymax*, *Tmax* and *ΔY* may also be affected by genetics. *M. giganteus* is a natural triploid hybrid between a diploid *M. sinensis* and a tetraploid *M. sacchariflorus* (Greef & Deuter, 1993). Because of its sterility and vegetative propagation, *M. giganteus* has been found to display very little genetic diversity and is therefore often treated as a unique genotype whereas differences can exist between clones in terms of morphological characteristics and yields (Clifton-Brown *et al.*, 2001; Zub *et al.*, 2011; Jezowski *et al.*, 2011). This information is however not available and would require isozyme and DNA studies as performed by Greef *et al.* (1997) and Hodkinson *et al.*(2002).

5. Conclusion

Analysing our *M. giganteus* European long-term yield database allowed us (i) to describe yield evolution across the whole crop lifetime and (ii) to characterize that evolution through key variables such as the maximum yield, the duration to reach that maxima and the decline rate. Maximum yields were found to be highly variable as well and this variability was explained by a climatic influences. *M. giganteus* yield is then determined by growth defining factors, rather than by growth limiting or reducing ones. Yields were also characterized by a strong inter-annual variability. Duration of the establishment phase was again variable and sometimes longer than what was previously suggested by the literature. That duration was strongly determined by the planting method. Model comparisons showed that yield evolution was best described when a decline hypothesis is included. Yet, decline intensity was quite variable: at some stands, yields remained nearly steady up to more than 20 years whereas other stands presented a severe decline. The overall trend is nevertheless a declining one. Various hypotheses related to crop management (fertilization, harvest) and climate were investigated but none could be validated.

Further work is needed to (i) understand the factors inducing yield decline and (ii) study whether that decline can be halted or reversed, for instance by modifying the fertilization or by revitalizing rhizomes through mechanical division. Yield evolution across time is a key element in any assessment work dedicated to a potential energy crop. Energetic viability, carbon mitigation potential and profitability hinge critically on them. Therefore our work could allow to precise such assessments. Our model could for example be coupled to an economical model to assess whether the yield decline intensity influences the crop profitability. In the same way, gathering information on commercial yields compared to experimental yields would be very valuable, as well as getting a better understanding of the yield variability during the ceiling phase.

Acknowledgments

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Chapitre 5.

Conception et évaluation de systèmes de culture à vocation énergétique

Designing and assessing energy oriented cropping systems

1. Introduction

The production of biofuels from agricultural feedstock causes heated discussions related to the possible environmental impacts of such biofuels (Crutzen *et al.*, 2007; Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Melillo *et al.*, 2009) and to possible threats to food security, due to land use dedicated to bioenergy instead of food production. As a consequence, the European Union has associated biofuel production targets with production sustainability criteria (Directive 2009/28/EC, 2009). In particular, a minimum saving of 35% of greenhouse gas emissions compared with the substitute fossil fuels was set, as well as constraints regarding biodiversity and soil organic carbon. Moreover, agricultural feedstock involved in the production of biofuels must complete the European regulation related to good agricultural practices.

Miscanthus x giganteus (hereafter referred as *M. giganteus*) is expected to produce high yields with low input requirements and is therefore often considered as one of the most promising agricultural feedstock to produce bioethanol (Lewandowski *et al.*, 2003; Heaton *et al.*, 2010). *M. giganteus* was therefore involved in studies aiming at assessing its potential to produce bioethanol while guaranteeing low environmental impacts. Several studies focused on the energy and/or on the GHG balance of (i) *M. giganteus* derived biofuel, comparing it with conventional fuels (Lewandowski *et al.*, 1995; Hillier *et al.*, 2009) or (ii) *M. giganteus* cultivation, comparing it with other potential energy agricultural feedstock (Lewandowski & Schmidt, 2006; Styles & Jones, 2007, 2008; St. Clair *et al.*, 2008; Angelini *et al.*, 2009; Hillier *et al.*, 2009). *M. giganteus* was included as well in life cycle assessments (LCA), which characterize impacts in terms of GHG emissions but also in terms of environmental impacts (*e.g.* euthrophication, acidification, ecotoxicity) or impacts on the human health (Monti *et al.*, 2009b; Fazio & Monti, 2011). Some studies dealt with the economics of the crop compared with other dedicated energy crops and food crops (Styles & Jones, 2008; Krasuska and Rosenqvist, 2011) while Smeets *et al.* (2009) studied both the economical and GHG performance of *M. giganteus* compared to switchgrass. Regarding the energy, GHG and environment aspects, these studies highlighted that *M. giganteus* outperformed food crops. Nevertheless, economic results differed among studies. Among energy crops, *M. giganteus* performed generally better than annual crops, while comparison with other perennial crops differed according to the studies.

Although those studies involved different feedstock and different methods, they displayed similar gaps. First of all, *M. giganteus* yield was always estimated on the basis of experimental yields (Lewandowski *et al.*, 1995; Lewandowski & Schmidt, 2006; Styles & Jones, 2007, 2008; Angelini *et al.*, 2009; Krasuska & Rosenqvist, 2011) or models based on experimental data (Clifton-Brown *et al.*, 2007; Hastings *et al.*, 2008, 2009; Smeets *et al.*, 2009; Hillier *et al.*, 2009). Assumptions were made to reduce experimental yields in order to account for management issues or harvest losses but without being based on data. Styles *et al.* (2008) used three yield assumptions (low, mid and high) but did not related them to soil characteristics or crop management techniques Using a statistical model developed by Richter *et al.* (2008), Hillier *et al.* (2009) simulated yield as a function of soil type but underlined that low yields tended to be overestimated and high yields underestimated. Smeets *et al.* (2009) used the MISCANMOD model (Clifton-Brown *et al.*, 2000; Stampfl *et al.*, 2007) but its predictive capacity was shown to be limited (Hastings *et al.*, 2009). Besides, *M. giganteus*, as well as the other agricultural feedstock involved in the various comparisons, were rarely included in cropping systems. Boehmel *et al.* (2008) – who compared *M. giganteus* with an energy cropping system based on oilseed rape, winter wheat and winter triticale – and Monti *et al.* (2009b) who compared *M. giganteus* with a food cropping system based on maize and winter wheat – make exceptions. Yet, based on the analysis of crop sequencing effects, Zegada-Lizarazu and Monti (2011) suggested that food crops could benefit from the introduction of energy crops in the crop sequence. Furthermore, GHG balance, environmental impacts and economic results of bioenergy crops would benefit from an assessment carried out not only at the crop scale but also at the cropping system scale to take into account of preceding crop effects induced by the integration of bioenergy crops into cropping systems.

Our study aimed therefore at (i) comparing *M. giganteus* with other potential biofuel agricultural feedstock (i) using multicriteria cropping system assessment as a methodological framework, and (ii) using data representative of production-scale fields managed commercially.

2. Materials and methods

2.1. The study area

Our study was carried out in the department of Côte d'Or, located in the Burgundy region in Centre-East France, around Dijon (350 km southeast from Paris). The region was chosen because about 450 ha of *M. giganteus* have been planted in commercial farms since 2009, becoming one of the French regions where this crop is the most widely spread. The region is characterized by a semi-continental climate with a mean annual rainfall of 744 mm and a mean annual temperature of 10.7°C (average from 1971-2000 at the Bretenières meteorological station).

We focused our study on two soil types located in two different small regions: (i) a deep loamy-clay soil (LC) located in an alluvial plain located in the South of Dijon, and (ii) a moderately deep calcareous-clayey soil (CC) located on a calcareous plateau in the North of Dijon, where the climate is colder due to the altitude (about 400 m above sea level). Besides temperature, LC and CC soils differed in terms of available soil water content (SWC): SWC averaged 150 mm for LC and 75 mm for CC. The cropping systems used by the farmers in the alluvial plain rely mainly on straw cereals (winter wheat and barley) and oilseed rape, while livestock rearing or fodder crops are scarce. Short crop sequences, mainly oilseed rape / winter wheat / winter or spring barley, are the most commonly practiced (Mignolet *et al.*, 2007). Cropping systems are similar on the plateau, except for livestock rearing and fodder crops which are more present. Alfalfa is significantly cultivated due to the presence of a dehydration plant.

2.2. Designing cropping systems using expert knowledge

In the aim of comparing various cropping systems dedicated to bioenergy, a step of cropping systems design was included in the study. Cropping system design relied on a workshop involving two kinds of experts: local experts, *i.e.* farm advisors from extension services in the study area, provided knowledge on local pedo-climatic conditions and crop management systems, while scientific experts provided more general knowledge on dedicated energy crops (including their environmental impacts) and on agricultural greenhouse gas emissions. Experts were divided into two groups, one by soil type. A set of constraints (Lançon *et al.*, 2008) had been determined before the workshop to orientate the design process. Following the European Directive on Renewable Energy, the main constraint identified was the reduction by 50% of greenhouse gas emissions. However, for the purpose of the workshop, this constraint was commuted from the biofuel production chain to the cropping system scale.

Additional constraints were related to (i) yield maintenance, and (ii) reduction of local environmental impacts (nitrate losses and pesticide use).

Experts were asked to build two categories of cropping systems based on energy feedstock hereafter named energy cropping systems: (i) cropping systems including *M. giganteus*, and (ii) cropping systems based on annual and/or pluri-annual dedicated or multiple product crops. Energy cropping systems were compared to two reference cropping systems which did not include energy feedstock: one corresponding to the most widespread practices in the studied region and one based on integrated management rules. The cropping system design included the choice of the crop sequence, the management of the intercrop periods as well as the design of the crop management system of each crop. As it is a long step, crop management design mainly focused on the practices that have major impacts on GHG emissions and water pollution, *i.e.* soil preparation, fertilization and crop protection. Experts described crop management design using previous work carried out in the studied region to characterize conventional management, low input management and without pesticide management (Guichard *et al.*, 2011).

Experts could include the following energy feedstock based on the possibility to estimate yields from local expertise and data: *M. giganteus*, alfalfa, cereals, and maize. For cereals, either the whole crop could be dedicated to energy production (dedicated crop), or only straw. For alfalfa, only stems were dedicated to energy production, the leaves being used as fodder (Lamb *et al.*, 2007; González-García *et al.*, 2010a). Cereals, when only straw are used to produce energy, and alfalfa were therefore called ‘multiple product crops’. Hereafter, the item ‘energy feedstock’ will refer both to dedicated crops and to the energy part of ‘multiple product crops’.

2.3. Simulating yields of crops within a cropping system

We used the PerSyst model (Guichard *et al.*, 2010, submitted; Annexe 5) to assess the yields of the crops included in the designed cropping systems. PerSyst is a cropping system model based on local expert knowledge and simple models which simulate the effects of crop sequence and crop management at a yearly time step. Yield is calculated as a function of limiting and reducing factors (van Ittersum and Rabbinge, 1997). Experts define a range of values possible as potential yield (*i.e.* when only climatic factors reduce yield) for each soil type of the studied area associated with a potential yield distribution. They also assess the yield reduction due to (i) the preceding crop effect, (ii) the frequency of crops affected by the same pests and diseases in the crop sequence, and (iii) the soil physical and chemical fertility. Yield is then further reduced using simple models if nitrogen supply does not cover the crop needs. Finally, the experts assess the yield reduction associated to management techniques (sowing period, crop protection, *etc.*).

As *M. giganteus* was recently introduced in the studied area, expert knowledge was not available. PerSyst was therefore parameterized for *M. giganteus* using the statistical model developed in **Chapter 4** and the commercial yield data analysed in **Chapter 2** to predict long-term yields: commercial yield data of farmers' fields planted in 2009 were added in the **Chapter 4** database as extra 'experimental units' and the parameters of the model were estimated for each farmers' field using the method described in **Chapter 4**. Only farmers' fields planted in 2009 were included in order to predict the inter-annual yields from the measurements of the first two years. We also checked through cross-validation that we could reasonably predict yields from two data standing for the two first harvests (see Annexe 3). Fields were divided into three groups in order to build three yield scenarios: *L*) low yields, *I*) intermediate yields and *H*) high yields. For each scenario, a yield range per year was defined based on the prediction made from the fields present in each group. *M. giganteus* yield was then predicted for each year as the mean of ten random samplings, as it is made for the potential yield of the other crops. Unlike the other crops, this yield did not represent a potential yield and was not further reduced since information on cropping sequence effect or management techniques effects were not available. However, based on the results of the yield gap analysis of *M. giganteus* implemented in the farmers' field network presented in **Chapter 2**, scenario *L* could be related either to shallow soils, or to fields where *M. giganteus* development during the plantation year was poor. Furthermore, fertilization was defined for each yield scenario.

Winter wheat straw yield is said to range between 50% and 75% of grain yield according to the variety and the harvest losses (UNIFA, 2009) in accordance with Gabrielle et Gagnaire (2008) We therefore assumed that winter wheat straw yield amounted for 63% of grain yield. Winter triticale straw amounted for 80% of grain yield under the assumption that the ratio straw / grain is higher for triticale (Jørgensen *et al.*, 2007). Based on local expert knowledge, alfalfa stem yield amounted for 50% of total alfalfa yield, which is consistent with the scarce available literature (González-García *et al.*, 2010a).

2.4. Multicriteria assessment of cropping systems based on a set of indicators

Multicriteria assessment of the designed cropping system included (i) assessment of the cropping system potential to produce food, (ii) economic assessment (production costs and semi-net margin), (iii) assessment of the contribution to global warming through an estimation of greenhouse gases (GHG) emissions, assessment of the energy performance and (iv) assessment of local environmental impacts. For each assessment field, indicators were calculated using PerSyst predicted yields and/or description of the management techniques (see hereafter). Assessment involved inputs and processes at stake until harvest. Cropping system results were displayed globally for each soil with a radar: relative scores were calculated for each indicator based on the best cropping system. Some indicators require to be maximized (*e.g.* semi-net margin) and others to be minimized (*e.g.* GHG emissions). In order to get a homogeneous representation, the latest were displayed through the complementary note (*i.e.* ‘1 – indicator score’): therefore, for each indicator, the higher the score, the better.

2.4.1 Assessment of cropping systems potential to produce food

The potential of cropping systems to produce food was assessed thanks to two indicators: the food efficiency (FOOD EFF) and the food capacity (CAP FOOD). FOOD EFF was computed as the ratio between the simulated yield with PerSyst and the potential yield parameterized in PerSyst. CAP FOOD was computed as the product of FOOD EFF and the ratio of food crop in the cropping system.

2.4.2 Economic assessment

Economic assessment of cropping systems relied on the estimation of the input costs in (including seeds, fertilizers, pesticides, and fuel costs) and of the semi-net margin (snM). snM was estimated as the difference between the gross product (depending on yield and product prices) and the input costs. Economic assessment was based on mean grain and input prices derived from the 2005-2009 period (UNIP, 2011): *e.g.* 125 € t DM^{-1} for winter wheat, 250 € t DM^{-1} for oilseed rape, 0.5 € per unit of N fertilizer, 0.8 € l^{-1} of fuel. Energy feedstock prices were based on *M. giganteus* price in the studied area, i.e. 73 € t DM^{-1} (Béjot, pers. comm.). For ‘multiple product crops’, input costs were allocated between both outlets using a mass allocation method. Costs related only to the production of the energy feedstock (*i.e.* additional harvest and fertilization costs related to straw exportation for cereals) were attributed only to it. Costs and snM per hectare were used to compare cropping systems. For energy feedstock, they were estimated per ton under the assumptions that yield was a good indicator of the energy yield.

2.4.3 GHG emissions and energy performance

Estimation of GHG emissions

GHG emissions were estimated as the sum of CO_2 and N_2O emissions following the IPCC Tier I method (IPCC, 2006b). CO_2emissions were separated between direct emissions related to fuel consumptions and indirect emissions related to input production. CO_2emissions were estimated as follows:

$$CO_2\ Emissions = \sum_i E_i * Q_i$$

Where: E_i is the emission factor of input *i*; Q_i is the quantity applied of input *i*. We used the emissions factors (for direct and indirect emissions) provided by GES'tim (Institut de l'Elevage, 2010). Inputs involved for indirect emissions were fertilizers (in kg ha^{-1}) and fuel (in l ha^{-1}).

N_2O emissions were separated between direct soil emissions, and indirect soil emissions. Direct N_2O emissions involved nitrogen supply to the soil through fertilization and crop residues. Indirect N_2O emissions related to NH_3 emissions and nitrate leaching were estimated based on the Indigo method (Bockstaller *et al.*, 1997). N_2O emissions were estimated with the same equation as for CO_2, except that Q_i stood for the amount of nitrogen (in kg N or kg N-NO_3^-). Emission factors were the one recommended by the IPCC (*e.g.* 0.001 kg N-N_2O per kilogram of N dose or kilogram of N contained in crop residues: IPCC, 2006). Assumptions were needed to estimate the amount of above-ground and below-ground residues produced by *M. giganteus* and their nitrogen content since the crop is not included in the IPCC database: they were based on Strullu (2011). Additional assumptions were also necessary for oilseed rape and sunflower: they were based respectively on CETIOM expertise (Robert, pers. comm.), on Corbeels *et al.* (2000) and Helmy and Fawzy-Ramadan (2009). For *M. giganteus*, we assumed that the below-ground biomass does not contribute to soil N_2O emissions during the crop life-span and contribute only when the crop is destroyed, following the recommendations made by the IPCC for forage crops (IPCC, 2006).

For 'multiple product crops', GHG emissions related to the production of the crop were allocated between both outlets using a mass allocation method. GHG emissions related only to the production of the energy feedstock (*i.e.* additional harvest and fertilization costs related to straw exportation) were attributed only to it. For energy feedstocks, GHG emissions were estimated per ton under the assumptions that yield was a good indicator of the energy yield.

Energy performance

Energy analysis of the different cropping systems was carried out using two indicators: the energy costs and the energy efficiency. Energy costs for input production included in our study were related to machinery fabrication and repair, fertilizer and planting material production, fuel consumption for the various operations (energy costs related to pesticides production were not included. Energy costs for delivering the production outside the field, for storage and drying were not calculated neither. Energy efficiency was calculated for energy feedstocks as the ratio between energy outputs (defined as the product of yield and low heating value) and energy inputs (energy costs). For 'multiple product crops', energy inputs related to the production of the crop were allocated using the same method than for GHG emissions.

2.4.5 Local environmental impact assessment

Local environmental impact assessment was based on (i) nitrate losses and (ii) on the pesticide treatment frequency index (TFI)

Nitrate losses

Nitrate losses during winter were assessed based on the Indigo method (Bockstaller *et al.*, 1997). They depend on the crop type, the soil cover during winter, the soil and weather conditions (rainfall and soil available water) and on nitrogen fertilizer rates: soil mineral nitrogen (snM) was calculated at harvest using crop type and fertilization and then, before the beginning of drainage (*i.e.* at the beginning of winter), using the soil cover during winter and soil mineralization since harvest. A leaching coefficient is estimated as a function of winter drainage, soil field capacity and soil depth (following Burns model: Burns, 1976). We used weather data from winter 1999-2000 after checking that this winter was not characterized by an extreme weather compared to the mean conditions in the area.

As *M. giganteus* was harvested at the end of winter, snM at harvest is not relevant to estimate nitrate leaching. We estimated snM at the beginning of winter (snM-BW) using the findings of **Chapter 3**. We showed indeed that soil snM-BW decreased when crop age, *i.e.* yield, increased. That decrease was particularly strong between the first and the second growth year. That correlation was explained by the stronger crop development, which allowed a stronger N and water uptake, as confirmed by the correlation between snM-BW and shoot density. Based on the data collected in **Chapter 2**, we estimated snM-BW reduction as a function of crop age: snM-BW decreased on average by 50% between the first and the second growth years (GY) and by 25% between the second and third ones. We then assumed that this decrease would be smaller for yield scenario a (30% between GY 1 and 2, 15% between GY 2 and 3) but still occurs between the third and fourth growth year at a rate of 15%. We used the data collected on LC and AC soils to set snM-BW at the end of the first growth year.

Pesticide treatment frequency index (TFI)

TFI is defined as the number of pesticide applications, multiplied by the ratio of the applied dose per hectare to the recommended dose (Jacquet *et al.*, 2011). It was estimated by the PerSyst model as a function of the crop management separately for insecticides (without considering molluscicides), fungicides, herbicides and growth regulators. For *M. giganteus*, TFI included only herbicides and was estimated from the data collected on the *M. giganteus* farmers' field network (**Chapter 2**) under the assumption that no herbicide was required between the third growth year and the destruction year. Management used to destroy the crop at the end of the crop life span was based on local expertise and involved herbicide and mechanical operations (Béjot, pers. comm.).

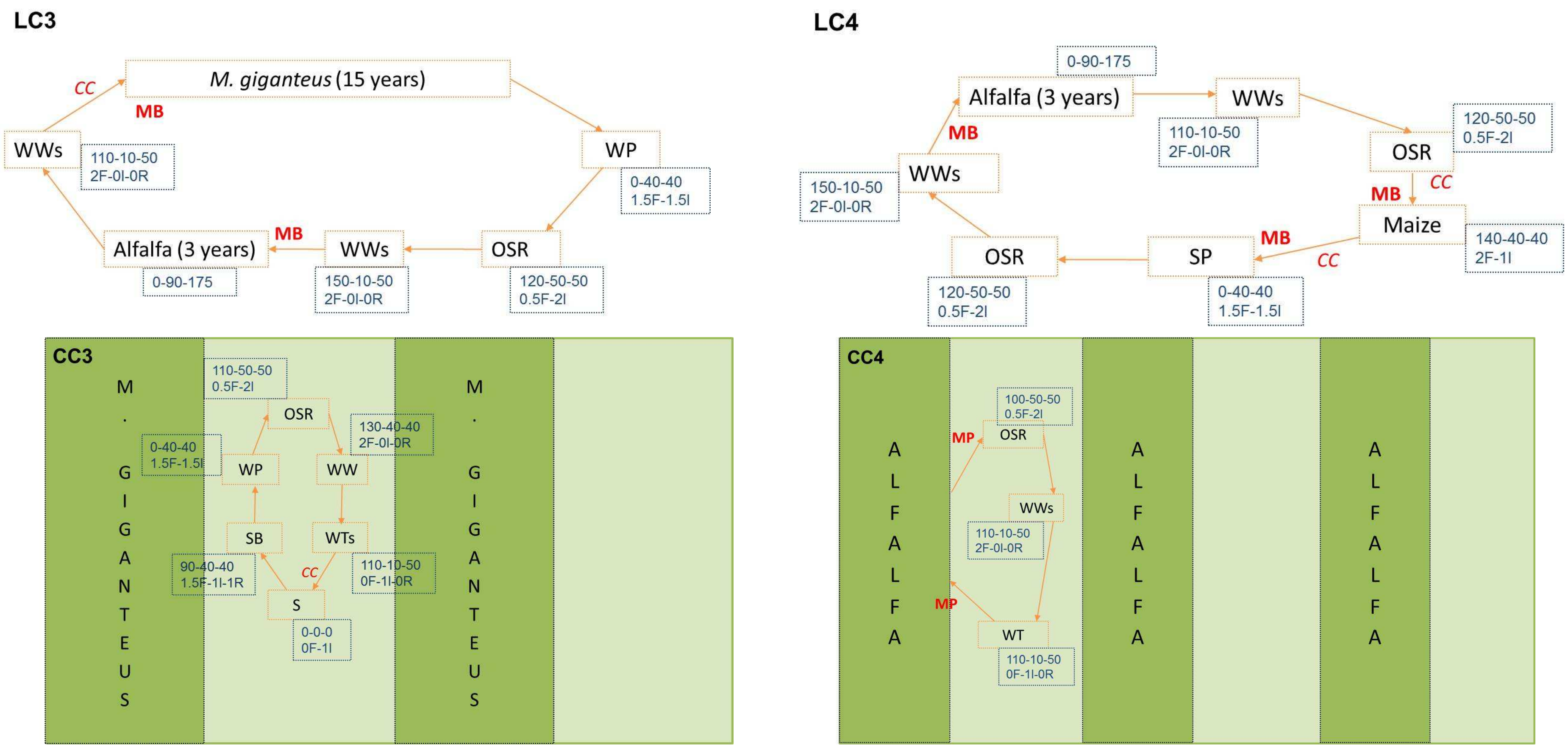


Figure 5. 1: Cropping system description.

WW: winter wheat; WP: winter pea; SP: spring pea; OSR: oilseed rape; WT: winter triticale; s: straw exported; MP: mouldboard ploughing; CC: cover-crop; Blue boxes: N-P-K rates (first line); number of fungicides F and insecticides I (second line)

3. Results

3.1. Cropping systems

For each soil, four cropping systems (CS) were designed (**Figure 5.1**, **Annexe 5**): two reference CS based only on food or fodder crops and two energy-oriented CS including several energy feedstock. On both soils, the reference cropping systems included the same crops. The 'conventional' reference CS (LC1 and CC1, also referred as CS1 when both CS are designed) were based on oil seed rape, winter wheat and winter barley. The 'integrated' reference CS (LC2 and CC2, or CS2) contained also the same three crops but included in addition two spring crops: sunflower and spring pea. In comparison with CS1, N rates were reduced in CS2: for instance, on deep loamy-clay soil (LC), N rates for winter wheat were reduced by 25 to 30 %. The addition of spring crops in the cropping sequence and the reduction of N rates allowed reducing crop protection: for instance, the number of fungicide treatments for winter wheat decreased from two treatments to one, and insecticide treatment as well as growth regulators were suppressed, in accordance with Loyce *et al.* (2012). Crop protection was also reduced because lower yield targets were accepted: no fungicide was thus applied on sunflower, which was also unfertilized. In CS 2, oil seed rape was preceded by pea to benefit from a positive preceding effect in terms of potential yield and N rate reduction as showed by Schneider *et al.* (2010). A cover crop was sown before every spring crop to reduce the risks of N losses. In CS1 and 2, a minimum of crops were ploughed. In CS1, only winter barley was ploughed while oilseed rape and winter wheat were planted with reduced tillage. Soil tillage for those crops was similar in CS2. However, sunflower and pea were ploughed. Such a choice for soil tillage reflected current practices in the study area and was driven by the will to maintain yields while reducing fuel costs, first for economic and time-saving motivations, then to reduce energy consumption and GHG emissions. Under the assumption that the soils had a correct availability of P and K, winter wheat and sunflower (for CS2) did not get any P or K fertilization.

Given the demands surrounding energy feedstock, the experts of the design workshop chose to build energy cropping systems using an integrated management framework. Following the aims of the workshop, two energy cropping systems were designed, one included *M. giganteus* (LC3) and one without *M. giganteus* (LC4). On LC soil, LC3 was designed targeting fields located in areas with environmental stakes, in particular regarding water quality. Apart from *M. giganteus*, alfalfa was regarded as an environmentally friendly crop and was therefore included in the cropping system. *M. giganteus* was preceded by winter wheat and followed by winter pea. A legume was chosen to follow *M. giganteus* given the

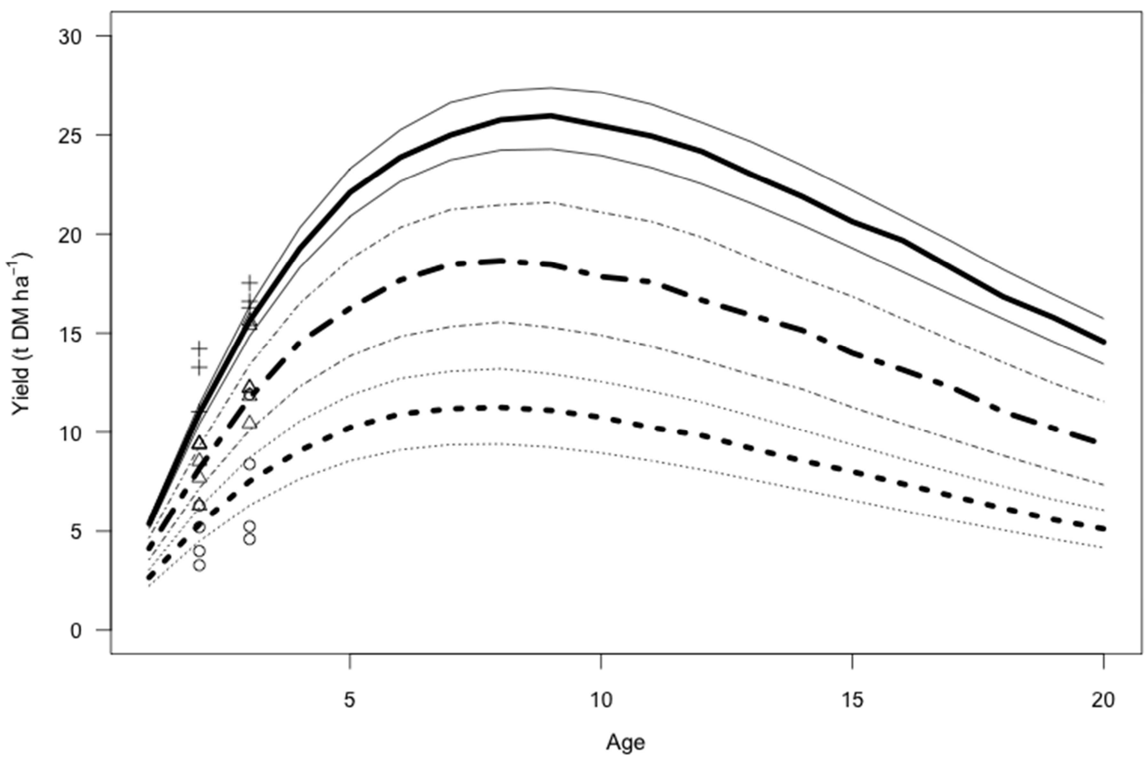


Figure 5. 2: Yield scenarios for *M. giganteus*.

Dotted lines stand for scenario LY, dotdash lines for scenario IY and solid line for scenario HY. Thick lines stand for the prediction while thin lines stand for minimum and maximum yields per year for each scenario. Circles, triangles and crosses stand respectively for the data used in the long-term yield prediction in scenarios LY, IY and HY.

high C/N ratio of *M. giganteus* residues (Amougou *et al.*, 2010). A winter legume was preferred to a spring legume in order to assure a faster development of the crop in spring so as to choke possible *M. giganteus* regrowth. As in CS2, pea was followed by oilseed rape cultivated without pesticides and winter wheat, which itself preceded and followed a three year alfalfa plantation. Apart from *M. giganteus*, wheat straw and alfalfa stems were also dedicated to energy production. Except for oil seed rape, crop management was designed with similar rules as in cropping systems '2' but adapted to the presence of *M. giganteus* and alfalfa as preceding crops: weeding was reinforced on pea while it was reduced on 'alfalfa wheat', along with N rate. Soil was ploughed before the plantation of alfalfa.

The second energy cropping system designed on LC soil (LC4) also included a three-year alfalfa based sequence surrounded by winter wheat. After the winter wheat following alfalfa ('alfalfa wheat'), oilseed rape preceded silage maize. A second legume was then included in the cropping sequence with spring pea, followed again by oil seed rape. Alfalfa stems, straw wheat and silage maize were dedicated to energy production. Crop management was designed using the same rules as in CS2 and accounting for the presence of alfalfa as in LC3. In LC3 as in LC4, exportation of P and K when straw was exported was compensated by an additional supply of 50 kg P and 10 kg K per ha. To simplify the assessment, we assumed that this additional supply was made on the crop whose straw was exported.

On the moderately deep calcareous-clayey soil (CC), the cropping system included *M giganteus* (CC3) was designed to take into account that fields on CC soils have large areas. Following agroforestry systems, experts decided to plant strips of *M. giganteus* alternating with strips based on an annual crops cropping sequence. The annual crop based cropping sequence included the sequence 'pea / oilseed rape / winter wheat' as in cropping systems '2' but winter pea was chosen instead of spring pea. Winter wheat was followed by winter triticale to include a low-input cereal. Sunflower, preceded by a cover crop, and spring barley finished the cropping sequence. Reduced tillage was applied for all crops. The 'strip spatial disposition' aimed at (i) minimizing the land required to produce energy, (ii) reducing the GHG emissions at the field scale by including a perennial crop, and (iii) benefit from a potential 'barrier effect' against wind and disease diffusion on the annual crop based cropping sequence.

A 'strip cropping system' without *M. giganteus* was also proposed and was based on alfalfa (CC 4). In CC 4, an alfalfa strip alternated with an annual crop sequence. Due to the pluri-annual character of alfalfa, strip nature in CS4 changed every three year: on a given strip, alfalfa was cultivated for three years and then followed by the annual crop sequence. Thus, the positive preceding effect of alfalfa mentioned by the experts regarding N rate, weeding but also soil structure and biodiversity, could benefit to the whole field. The annual crop sequence was based on oil seed rape (following alfalfa), winter wheat and winter triticale.

In addition, this spatial pattern was described as a possible lever to favor oil seed rape auxiliaries. Alfalfa stems, wheat straw and triticale were used for energy production. Triticale was harvested immature (stage ‘milky grain’) in order to sow alfalfa at the beginning of July. The whole crop was dedicated to energy production. Crop management was design with similar rules as in CC3 and adapted to the presence of alfalfa as in LC4.

3.2. Yield assessment

3.2.1 Energy dedicated crop and multiple product crop yields

On LC soil, three scenarios were built to describe *M. giganteus* yields, summarizing the information on commercial yields gathered in the farmers’ field network in **Chapter 2** (**Figure 5. 2**). Scenario *I* was based on ‘mean fields’, that is to say fields where observed yields ranged between 6 and 10 t DM ha^{-1} for the first harvest (second growth year) and between 10 to 16 t DM ha^{-1} for the second harvest. Seven fields among the sixteen observed belonged to that group. Maximum predicted yield reached 18.8 t DM ha^{-1} for that scenario while mean predicted yield amounted 14.7 t DM ha^{-1}. Scenario *H* was based on the three fields with the highest observed yields, which exceeded respectively 10 and 16 t DM ha^{-1} for the first and second harvest. Scenario *H* was characterized by a maximum predicted yield of 25.8 t DM ha^{-1} and a mean predicted yield of 20.6 t DM ha^{-1}. Scenario *L* was based on three low yielding fields where observed yields were lower than 6 and 10 t DM ha^{-1}, respectively for the first and second harvest years. Maximum and mean predicted yields were respectively 11.4 and 8.9 t DM ha^{-1}. Three particular fields with yields lower than 3 t DM ha^{-1} for the first harvest were not included in any group. One of those fields, planted close to a well water, could not be weeded chemically. The field was choked by weeds during the plantation year leading the farmer to crush it during summer. First harvest yield was therefore low (2.7 t DM ha^{-1}). However, the field was successfully mechanically weeded during the second and third growth year and yield increased by 4.5 between the first and second harvest. The two remaining fields were characterized by a low and very irregular planting density at the end of the first growth year. After the first harvest, rhizomes were mechanically divided in an attempt to increase planting density. It is therefore difficult to predict how those fields will evolve in the years to come.

Data on CC soil were insufficient to build yield scenarios due to a small number of fields which was even more reduced by establishment failure or fields where crop development was not enough to make the harvest profitable. Based on the scarce data available, we designed two yield scenarios with the help of the LC scenarios. Scenario CC-*Y* was a pessimistic one and relied on the lower boundary of LC-*Y*: it was characterized by a maximum predicted yield of 9.4 t DM ha^{-1} and a mean predicted yield of 7.4 t DM ha^{-1}. Scenario CC-*Y* was more optimistic and used the upper boundary of LC-*Y*: maximum predicted yield amounted

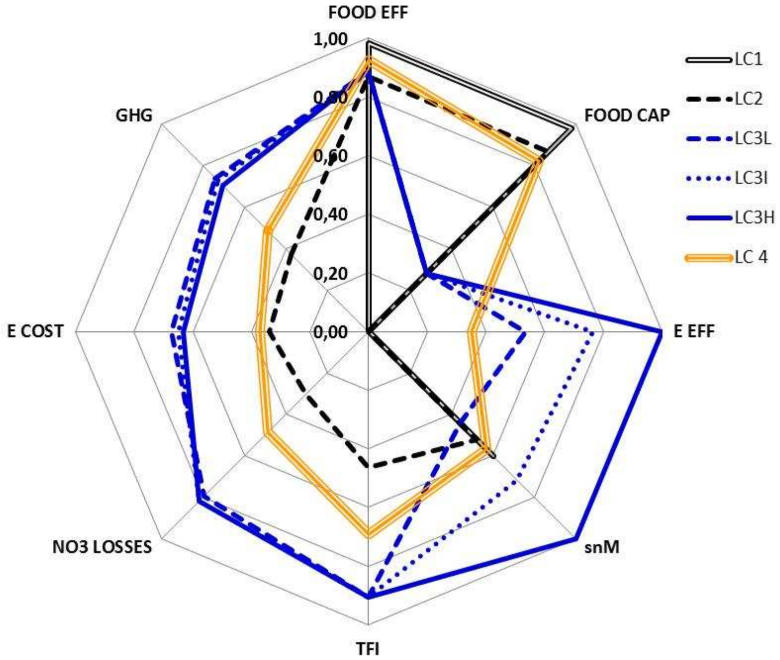
13.2 t DM ha^{-1} while mean predicted yield was 10.1 t DM ha^{-1}.Thesescenariowere consistent with the few data available on that soil: about 3.7 t DM ha^{-1} for a two-year old *M. giganteus* and 7.3 t DM ha^{-1} for a three-year old crop.

On LC, energy maize yielded 16 t DM ha^{-1}: it was thus a bit higher than *M. giganteus* mean yield in scenario 2. Maize yield stood for 85% of the potential maize yield parameterized on that soil: the decrease between potential yield and predicted yield was related to N rate. Alfalfa stems represented half of total alfalfa yield and amounted on average for the three years 5.7 t DM ha^{-1}. Alfalfa yield amounted for 93% of alfalfa potential yield: the small difference between both yields was related to the 2-cut regime used in the cropping systems. Winter wheat straw yield was on average 5.3 t DM ha^{-1}, *i.e.* about 63% of grain yield. Ratio between predicted yield and potential yield for winter wheat averaged 91.5% and was related to crop management. It was higher for 'alfalfa wheat' thanks to the positive preceding effect of alfalfa. On CC, energy triticale yielded 10.5 t DM ha^{-1}which is similar to *M. giganteus* mean yield in scenario CC-*H*. Alfalfa stem yield was on average 4.7 t DM ha^{-1}. Winter wheat straw yield was equal to 3.9 t DM ha^{-1} while winter triticale straw yield was 4.5 t DM ha^{-1}, *i.e.* 75% of grain yield. Ratio between predicted yields and potential yields were similar than those on LC soil for alfalfa and winter wheat. Winter triticale predicted yield amounted 87% of the potential yield: that reduction was related to a negative rotational effect (winter triticale being a 'second cereal') and to crop management.

3.2.2 Food/fodder crop yields

On LC soil, oil seed rape yield averaged 3.7 t DM ha^{-1} but ranged from 2.8 t DM ha^{-1} to 4.2 t DM ha^{-1}, which was considered as the potential yield by the actors involved in the design process. Oilseed rape in LC2 yielded slightly more than oil seed rape in LC1 thanks to the positive rotational effect of pea. In LC4, oil seed rape was preceded by winter wheat and yield was reduced as a consequence of the integrated management. Oil seed rape in LC3 got the lowest yield although it was preceded by pea because of the pesticide free management chosen. With 8.7 t DM ha^{-1}, winter barley in LC1 was equal to the potential yield. In LC2, winter barley yield amounted 85% of the potential. Sunflower was included only in LC2 and predicted yield amounted 69% of the potential yield due to a fertilization free management (yield = 2.2 t DM ha^{-1}). In LC2 and 4, spring pea yields amounted 93% of the potential yield (yield = 5.0 t DM ha^{-1}) while winter pea included in LC 3 amounted 95% of the potential yield (yield = 5.3 t DM ha^{-1}). As winter pea followed M. giganteus in LC3, management was not much lightened, especially regarding weeds.

a)



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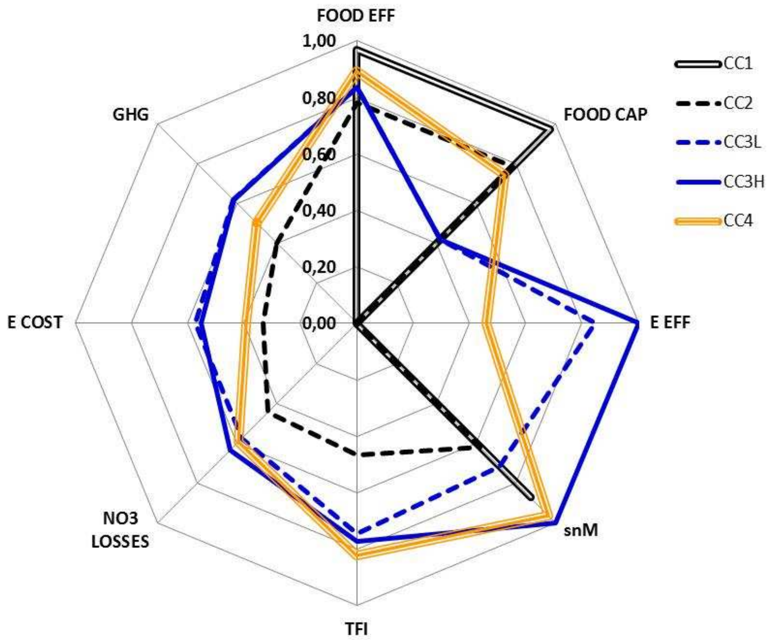


Figure 5. 3: Cropping system multicriteria assessment: a) LC soil; b) CC soil.

FOOD EFF: Food efficiency; FOOD CAP: Food capacity; E EFF: Energy efficiency; snM: Semi-net Margin; TFI: Treatment Frequency Index; NO3 LOSSES: Nitrate losses; E COST: Energy costs; GHG: Greenhouse gases emissions

LC3L: LC3 with *M. giganteus* yield scenario ***L*****,** etc.

On CC soil, potential yields were reduced by about 25% compared to LC soil. Ratio between predicted yields and potential yields were on average similar for oilseed rape, except for the one sown after alfalfa (CC4), and for pea. Losses due to management were higher for sunflower (52% of potential yield).Predicted spring barley yield amounted 92% of the potential yield.

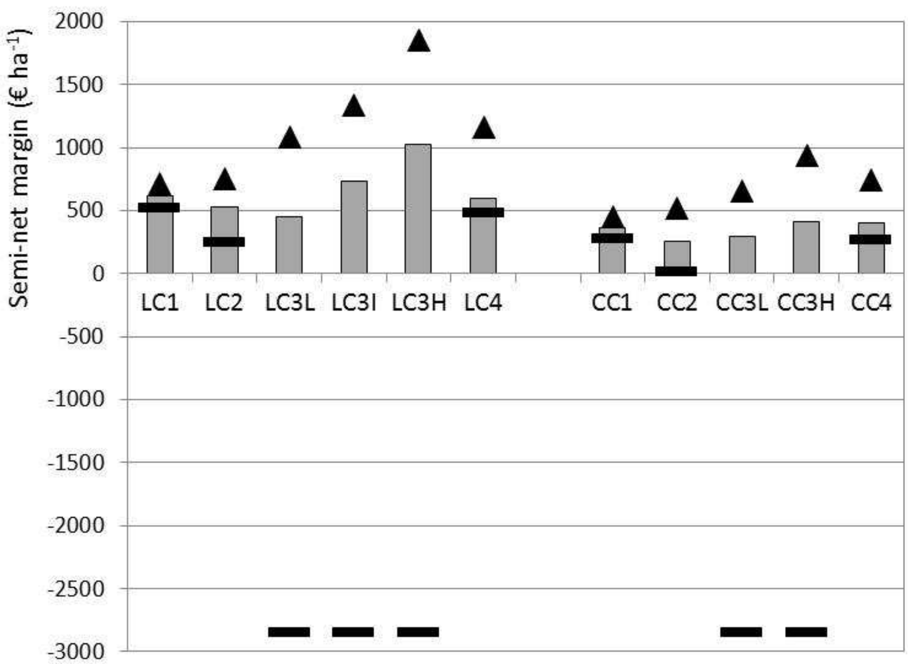
3.3. Multicriteria assessment of the cropping systems

Figure 5. 3 enabled to compare all cropping systems on a hectare basis according to soil type. Although cropping systems were designed for each soil type, we can separate for each soil a cropping system based on *M. giganteus* (hereafter referred as CS3) and an energy cropping system based on other energy feedstock (hereafter referred as CS4). CS3 differed by the weight of *M. giganteus* in the cropping system. CS4 included alfalfa and additional energy feedstock according to each soil type. All cropping systems were characterized by a good food efficiency equal or higher than 80%. Food capacity was well maintained in CS4 where only one dedicated energy crops was included. On LC soil, food capacity of LC3 was very low since the cropping system was mostly based on *M. giganteus*. It was higher on CC3 since it was composed half by *M. giganteus* and half by an annual crop sequence.

On LC soil, LC3 displayed the best profile regarding energy efficiency, environmental impacts (TFI and nitrate losses) and GHG emissions. Energy efficiency as well as semi-net margin (snM) depended strongly on *M. giganteus* yield scenarios. However, snM was the only indicator where the ranking among cropping systems relied on *M. giganteus* yield assumption. Ranking for energy efficiency was similar on CC soil. On the whole, results on CC soil were much tighter and CC3 was even surpassed by CS4 in terms of TFI. Ranking regarding snM and energy efficiency depended again strongly on *M. giganteus* yield scenarios.

3.1.1 Economic assessment

On LC soil as on CC soil, results of the cropping system comparison were highly dependent on the assumptions made for *M. giganteus* yields (**Figure 5. 4a**). LC 3 based on *M. giganteus* yield scenario c, *i.e.* the highest yield assumption (LC3-*H*) was characterized by the best semi-net margin (snM). LC3-*I* (with *M. giganteus* yield scenario *I*) snM was close to the one of LC4. LC3-*L* (*i.e.* the lowest yield assumption) was less profitable than LC1 and LC2. On CC soil, CC3-*H* was characterized by the same snM than CC4, while CC3-*L* snM was similar to CC2 snM. CC1 snM was intermediate between both duos. Cropping systems also differed by snM between-crop variability. On both soils, CS1 were characterized by the smallest variability, while CS3 were characterized by the highest variability due to the presence of *M. giganteus* which required a high investment at planting (2800 € per ha) while a)



b)

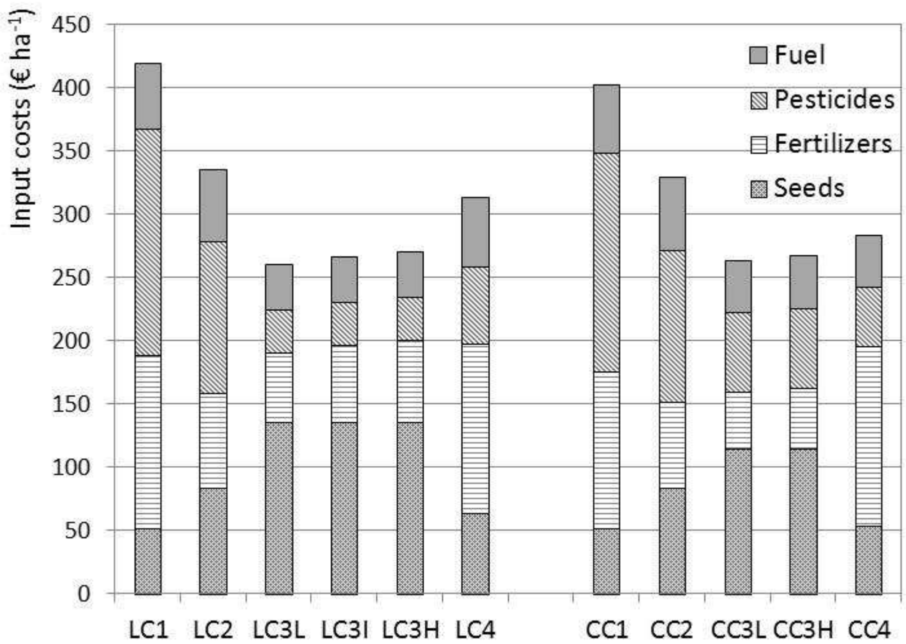


Figure 5. 4: Economic assessment of cropping systems (€ ha^{-1}): a) semi-net margin, b) production costs.

Bar plots stand for the mean value of each cropping system. Horizontal bars stand for the lowest value and triangles for the highest.

the crop is not harvested at the end of the plantation year and does not enter in full production until a few years. CS2 and 4 snM variability was intermediate due to the presence of ‘diversifying crops’ such as sunflower or pea which got lower snM than cereals or oilseed rape. The lower snM on CC soil were related to lower gross product due to lower yields rather than higher costs. Costs on CC soil were even slightly smaller due to smaller N rate related to smaller yield potentials (**Figure 5. 4a**).

On both soils, costs structure was different between cropping systems (**Figure 5. 4b**). In comparison with CS1, CS2 seed costs were higher but fertilization and pesticide costs were largely lower leading to overall lower costs. Pesticide costs were even more reduced in CS4 that was based on quasi pesticide free alfalfa. However, fertilization costs were higher due to the high needs of alfalfa in terms of P and K fertilization. For CS3, costs were almost similar among the *M. giganteus* yield scenarios since fertilization costs were the only yield related costs. On LC soil, CS3 got the lowest costs since it was mostly *M. giganteus* based. On CC soil, due to the lower weight of *M. giganteus* in CC3 (compared to LC3) and to the higher weight of alfalfa in CC4 (compared to LC4), costs of CC3 and 4 are similar. Good performance of alfalfa-based CS were related to the low costs but also to the high price of alfalfa leaves (110 € t DM^{-1}).

3.2.1 GHG emission and energy cost assessment

On both soils, CS3 based on M. giganteus produced the lowest amount of GHG, although the difference was emphasized on LC soil due to the prevailing weight of *M. giganteus* in LC3 (**Figure 5. 5**). As for costs, GHG emissions were almost identical among *M. giganteus* yield scenarii since GHG related to N fertilization and plant residues were the only yield related emissions. CS1 was characterized by the highest GHG emissions while CS2 and CS4 produced intermediate emissions. On LC soil, GHG emissions were reduced by 40% between LC1 and LC2, 50% between LC1 and LC4 and 75% between CS1 and LC3. Reduction rates on CC soil were similar except between CC1 and CC3: GHG emissions were only reduced by 60% due to the lower weight of *M. giganteus* in CC3. Nitrogen fertilization, through indirect CO_2 emissions during the fertilizer production and direct N_2O emissions from the soil was the main source of GHG. Difference between cropping systems were therefore related to the reduction of N rate and to the weight of crops that were not N fertilized, *i.e.* legumes (pea and alfalfa) but also sunflower. Aside CS3, GHG emissions on CC soil were slightly lower than on LC soil: that difference between soil types were related to the lowest N rates used on CC soils (due to the lowest yield potentials) although indirect N_2O emissions, mostly caused by N leaching, were higher.

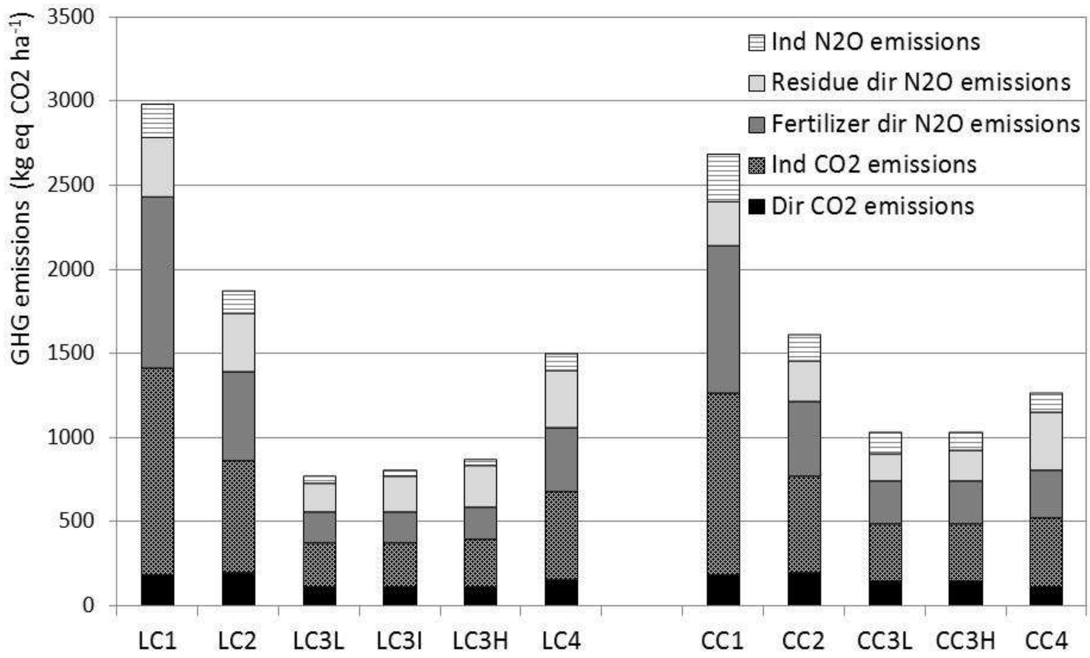


Figure 5. 5: GHG emissions estimated at the cropping system scale (kg eq CO_2 ha^{-1}).

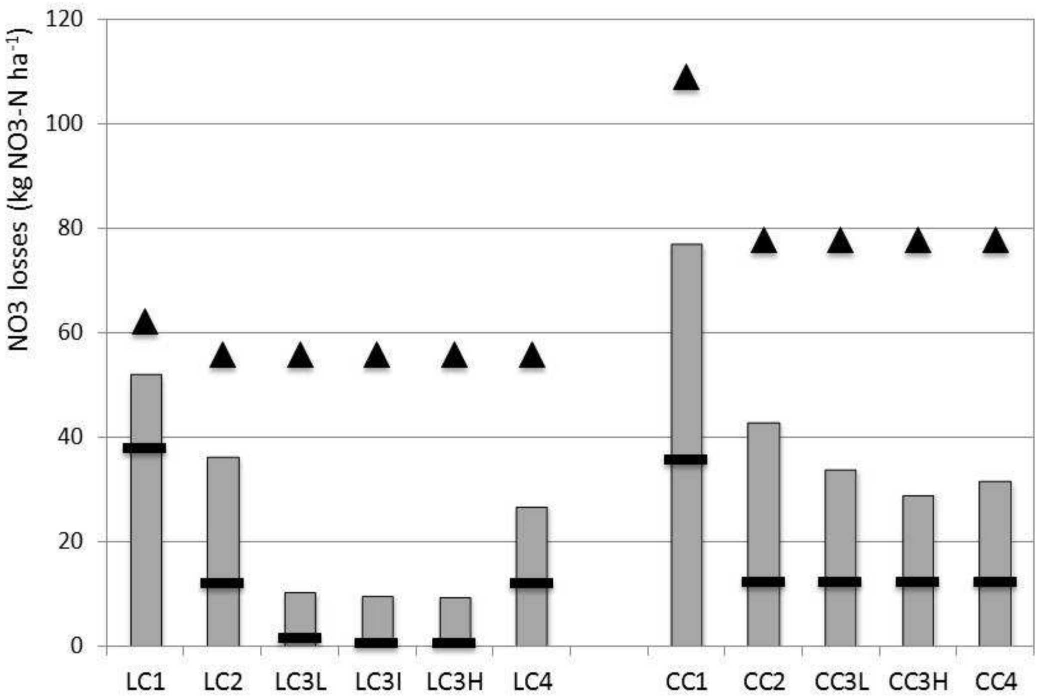


Figure 5. 6: Assessment of nitrate losses (kg N ha^{-1}).

Bar plots stand for the mean value of each cropping system. Horizontal bars stand for the lowest value and triangles for the highest.

Classification of the cropping systems regarding energy costs was similar (**Figure 5. 3**). Energy costs were for instance reduced by 70% between LC1 (mean energy costs = 12.4 GJ ha^{-1}) and LC3 (mean energy costs = 4.0 GJ ha^{-1}), by 45% between LC1 and LC4 and by 40% (mean energy costs = 8.2 GJ ha^{-1}) between LC1 and LC2 (mean energy costs = 6.9 GJ ha^{-1}). Energy cost structure was close to CO_2 emission structure although costs related to fuel consumption during cropping and harvesting operations had a higher weight than direct CO_2 emissions during the same operations.

3.2.1 Environmental assessment

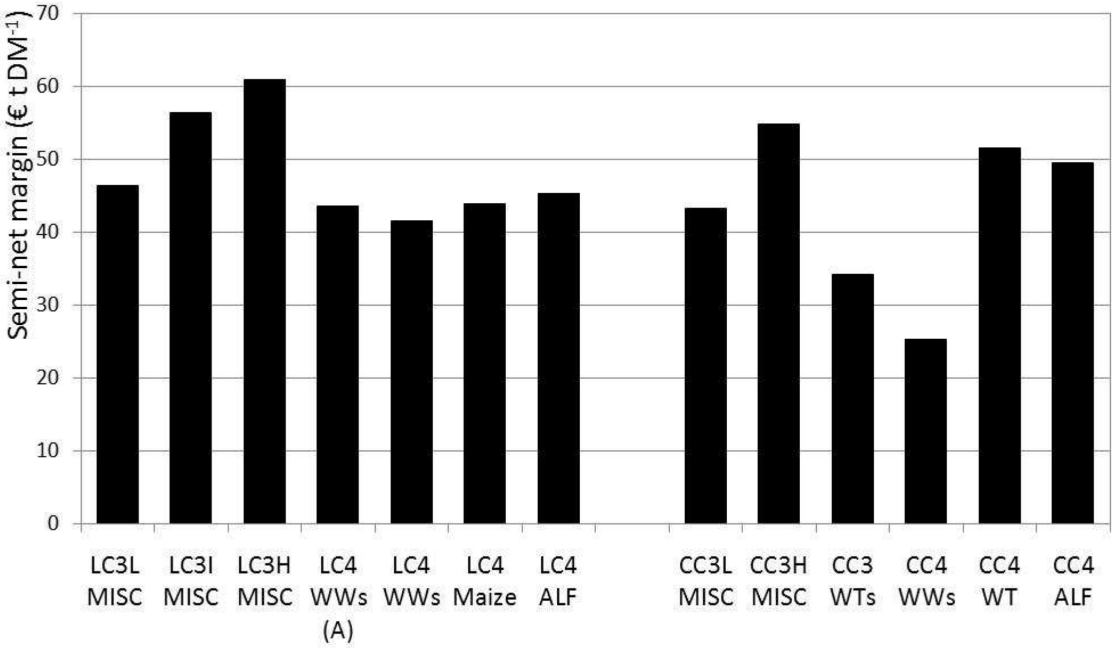
Nitrate leaching

On LC soil, LC1 presented the highest loss of nitrates and LC3 the lowest, while LC2 and LC4 were intermediate (**Figure 5. 6**). N rate reduction and insertion of non N-fertilized crops (pea, sunflower) explained the decrease in nitrate losses between LC1 and LC2. LC4 nitrate losses were even more reduced thanks to the presence of a non-fertilized pluri-annual crop, alfalfa. LC3 displayed the highest between-crop variability. Quasi-null nitrate losses resulted from the presence of *M. giganteus* in the cropping system. On the opposite, maximum losses were not due to the higher nitrate losses occurring after the plantation of *M. giganteus* compared with the following years (**Chapter 3**) but to the annual crops also included in the cropping system. On the whole, maximum losses were similar across cropping systems that differed by the mean and the minimum losses. Nitrate losses were on average higher on CC soil since it is a shallower soil. CC1, CC2 were ranked as their LC *alter ego*. On the other hand, CC3 and CC4 got similar results.

Pesticide pressure (as indicated by the treatment frequency index TFI)

TFI was among the indicators that were not related to *M. giganteus* yields (**Figure 5. 3**). On LC soil, LC1 was characterized by the highest TFI and LC3 by far by the lowest TFI: TFI was reduced by 95%between LC1 and LC3, mostly thanks to the quasi ‘pesticide free’*M. giganteus*. A longer cropping sequence including spring crops allowed a TFI reduction of 55% between LC1 and LC2. The addition of alfalfa in LC4 allowed a higher reduction of 70%. The reduction between CC1 and CC2 was similar. The rest of the comparison was however different on CC soil since with a reduction of 80%, AC4 was the cropping system allowing the highest TFI reduction. CC3 was associated with a 70% TFI reduction. This difference between soils was related to the lower weight of *M. giganteus* compared to LC3 and to the higher weight of alfalfa in CC4 compared to LC4.

a)



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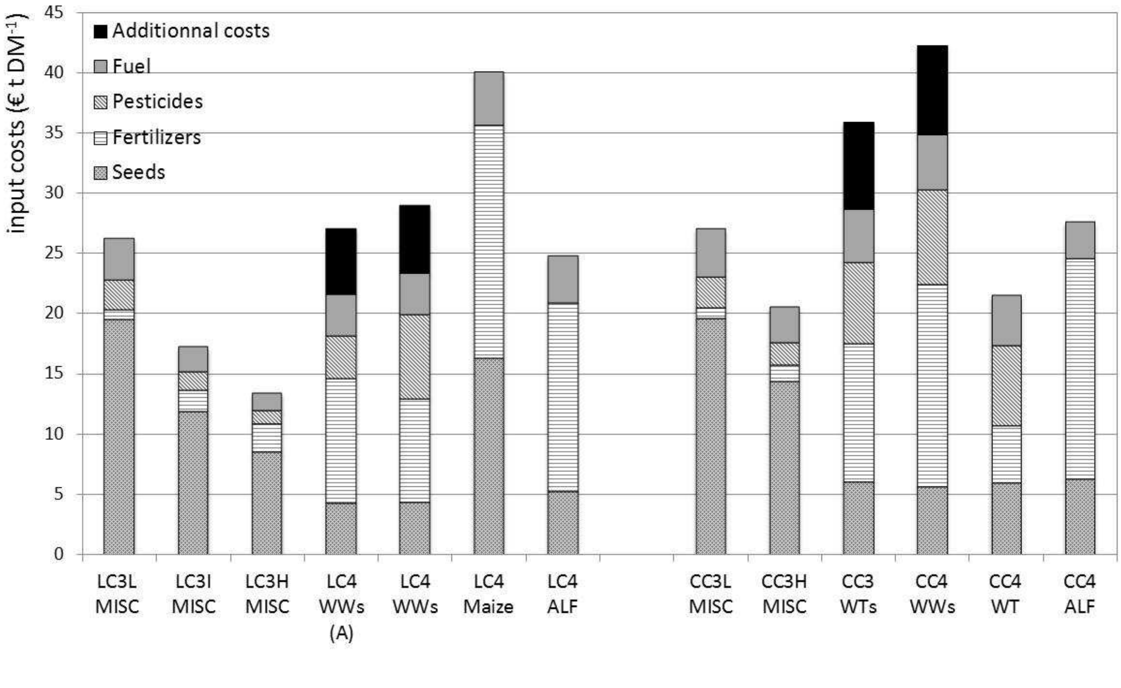

Figure 5. 7: Economic assessment of energy feedstock (€ t DM^{-1}): a) semi-net margin, b) production costs.

MISC: *M. giganteus*; WWs: winter wheat straw (A: with alfalfa for preceding crop); ALF: alfalfa; WTs: winter triticale straw; WT: winter triticale

3.4. Assessment at the energy feedstock scale

3.2.1 Economic assessment

On LC soil, *M. giganteus* snM ranged between 48 and 62 € t DM^{-1}according to the yield scenario, which was higher than maize and alfalfa stem snM (**Figure 5. 7a**). However, for yield scenario *LY*, *M. giganteus* snM was only slightly higher than maize and alfalfa snM. snM of winter wheat straw were similar to *M. giganteus* snM for scenario *IY* when winter wheat followed alfalfa and slightly lower otherwise. On CC soil, dedicated winter triticale, winter triticale straw, winter wheat straw as well as alfalfa stems displayed lower snM than *M. giganteus* when the latest got the best yields and lower otherwise.

On LC soil, *M. giganteus* displayed the lowest costs per ton when yields were intermediate and high (**Figure 5. 7b**). When yields were low, *M. giganteus* costs turned out to be intermediate between the costs related to the production of alfalfa stems and the ones related to the production of winter wheat straw. Alfalfa for preceding crop allowed a small decrease in winter wheat straw costs thanks to the lower N rate. Maize was characterized by the highest costs per ton, due to higher seed costs. Although fuel and seed costs of alfalfa stems were among the smallest, total costs were relatively high due to the high P and K fertilization costs. *M. giganteus* costs differed from the other crops by the high weight of seed costs caused by the use of rhizomes. Due to the lower yields on CC soil, ranking was different. Dedicated winter triticale performed very well since it displayed costs quasi similar to the ones of the high yielding *M. giganteus*. Alfalfa stem costs looked closely to the low yielding *M. giganteus* while winter wheat and triticale straw presented the highest costs per ton. On CC soil as on LC soil, additional costs related to the exportation of straw (*i.e.* additional harvest and fertilization costs) represented between 20 and 25% of total costs.

3.2.1 GHG and energy assessment

On both soils, *M. giganteus* with any yield scenario displayed the lowest GHG emissions while alfalfa stems were the second lowest (**Figure 5. 8**). On LC soil, GHG emissions per ton resulting from the production of maize were similar to the one from winter wheat straw when winter wheat was preceded by alfalfa. Maize higher yield was compensated by the allocation of GHG emissions for straw. Otherwise, winter wheat straw GHG emissions were 20% higher. On CC soil, dedicated winter triticale ranked third, closely followed by winter triticale straw and winter wheat straw. Any crops assessed here allowed a dramatic decrease in GHG emissions compared to first generation crops such as oil seed rape or winter wheat, even when the latest are part of integrated cropping systems (**Table 5. 1**). GHG emission sources differed severely between crops. While maize, triticale and straw GHG emissions were strongly

Table 5. 1: GHG emissions from first generation crop estimated from the assessment results.

Soil	LC	CC
Crop	GHG emissions (kg eq CO_2 t DM^{-1})	
OSR	705	849
OSR	515	637
WW	388	451
WW (A)	340	399

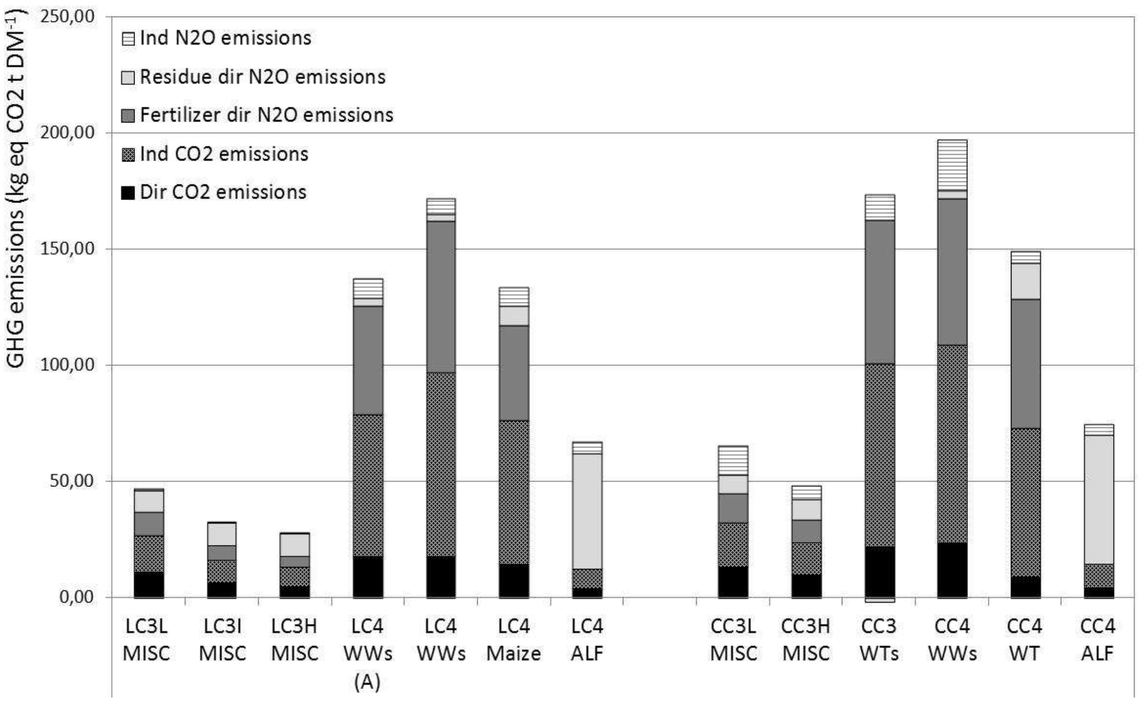

Figure 5. 8: Estimation of GHG emissions at the energy feedstock scale.

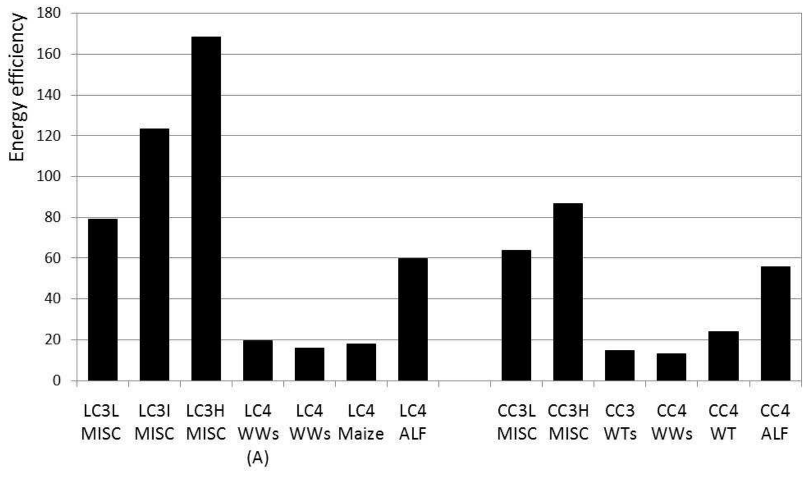

Figure 5. 9: Energy efficiency of the different energy feedstocks.

related to fertilizers through CO_2 indirect emissions and soil N_2O emissions, alfalfa GHG emission profile was strongly determined by soil N_2O emissions due to the high nitrogen content of alfalfa residues. GHG emissions associated to *M. giganteus* were mostly indirect CO_2 emissions and direct soil N_2O emissions. The latest are strongly caused by the high amount of biomass accumulated in the soil during the crop lifespan that increase the amount of soil nitrogen when the crop is destroyed.

Energy feedstock ranking regarding energy efficiency were similar to GHG emissions. On both soils, low energy costs allowed *M. giganteus* to display the best energy efficiency, even for the lowest yield assumption (**Figure 5. 9**). On LC soil, winter wheat straw got the worse energy efficiency. Alfalfa as preceding crop improved slightly wheat straw energy efficiency, making it similar to the one of dedicated maize. On CC soil, winter wheat straw energy efficiency was the lowest as well. Winter triticale straw scored between winter wheat straw and dedicated triticale. On both soils, alfalfa stems were the feedstock with the second best energy efficiency but were much closer from straw and dedicated crop results than from *M. giganteus*.

4. Discussion

During the workshop where the cropping systems were designed, the experts were divided into two groups and each group dealt with one of the studied soil. As a consequence, the differences between the designed cropping systems were related to constraints specific to each pedo-climate (soil water availability, field size, *etc.*) but also to the experts present in each group. However, as the logic behind each cropping system was made explicit, the assessment results can be extrapolated beyond each soil type and the expert panel. Hereafter, we will first highlight that methodological issues make it difficult to compare our study with other assessment studies. Then, we will discuss our results at the energy feedstock scale and at the cropping system scale. Finally, the main uncertainties related to our findings will be discussed.

4.1. Methodological issues related to assessment studies

As already noticed in several assessments dedicated to *M. giganteus* (Styles & Jones, 2008; Monti *et al.*, 2009b; Krasuska & Rosenqvist, 2011; Fazio & Monti, 2011), the results depended strongly on the methodological framework, in terms of assessed system boundary and assumptions necessary to carry out the assessment. Here, we focused on the inputs and processes at stake until harvest, differing therefore from cradle-to-farm gate assessments (Styles & Jones, 2007, 2008; St. Clair *et al.*, 2008; Krasuska & Rosenqvist, 2011) and cradle-to-grave assessments (Fazio & Monti, 2011).

Cradle-to-farm gate assessment includes additionally biomass transport between the field and the farm and storage in the farm. Such assessments required extra assumptions on the distance between the field and the farm, which does not depend directly on any cropping system characteristics. However, as highlighted in **Chapter 2**, distance to the farm is one of criteria guiding the choice of a field to plant *M. giganteus*. Cropping systems including that crop could therefore display higher transport costs. Nevertheless, **Chapter 2** highlighted also that *M. giganteus* was preferentially planted in small fields, fields with irregular shape or fields located in areas with environmental issues, which does not rely on the distance between the field and the farm. Based on the example of giant reed (*Arundo donax*) and fiber sorghum, which are harvested at high moisture contents, Fazio and Monti (2011) showed that storage could have a severe impact on the assessment results: replacing industrial drying processes by natural field drying allowed 40% lower impacts. Storage was not included in our analysis. However, the energy feedstock included dried naturally on the field (*M. giganteus,* straw) or were harvested as silage crop. Cradle-to-grave assessment includes the transformation of the biomass into an energy carrier, as well as the distribution and the use of the energy carrier.

However, Fazio and Monti (2011) highlighted that cradle-to-grave outcomes mirrored the cradle-to-farm gate results.

Within our system based on ‘cradle-to-harvest’ boundaries, we made some simplifications. Cropping and harvest interventions were taken into account through fuel consumptions, that is to say that machine maintenance and depreciation, as well as labor were not included. We assumed that those elements are better reasoned at the farm scale rather than at the cropping system scale. Beside, crop protection was described in terms of treatment number and treatment qualitative description (normal *vs.* ‘light’). Based on this information, the PerSyst model estimated TFI and then economical costs based on a crop parameterization of the cost per TFI point (Guichard *et al.*, 2011). Such a parameterization was not available for energy costs and GHG emissions: the energy costs and GHG emissions related to the production of pesticides were therefore not included in the assessment while only application costs and emissions were taken into account. Based on the GHG emission estimations of St. Clair *et al.* (2008), we can nevertheless confirm that emissions related to the production of pesticides are much lower than the ones related to the production of fertilizers on a hectare basis: they are for instance seven times lower for oilseed rape.

Due to these methodological differences, results can hardly be compared between various assessments, at least on a quantitative point of view. However, when assessments include several crops, it is relevant to assess whether ranking are similar. In any case, identifying which assumptions cause the biggest difference is also valuable. Compared to most assessments dedicated to energy crops, our study also differed by the focus on the cropping system scale. Monti *et al.* (2009) did include a cropping system based on winter wheat and maize as reference scenario of conventional cropping systems in their cradle-to-farm gate LCA but did not provide any justification of that choice. No integrated cropping systems were present in the comparison. Boehmel *et al.* (2008) compared experimentally three perennial energy crops, willow, *M. giganteus* and switchgrass, with an annual cropping system based on continuous maize and an annual cropping system based on oil seed rape, winter wheat and winter triticale. Variations in soil tillage and N rate were included in the factorial experimental design but this is not equivalent to the reflection carried out in our workshop to design integrated cropping systems.

Before discussing the assessment results, we shall notice that one of the cropping system proposed during the workshop had to be modified. The first version of CC4 was slightly different since alfalfa was sown within a maize crop. However, during the parameterization of PerSyst, maize was not parameterized on that soil because growing that crop was seen as too risky given the moderate soil water content of the soil. We therefore suppress the sowing of alfalfa within a maize crop and assessed a cropping system with alfalfa sown as a sole crop in summer.

4.2. Comparison of the energy feedstock

Comparing *M. giganteus* with the other energy feedstock included in our study involved to separate assessment fields where the results relied on the yield assumptions made for *M. giganteus* from the other assessment fields.

On both soils, the first category of assessment fields contained GHG emissions, where *M. giganteus* clearly outperformed the other crops, except alfalfa. However, the difference between M. giganteus and alfalfa was bigger on a hectare basis (data not shown). Styles and Jones (2007), Saint Clair *et al.* (2008), Hillier *et al.* (2009), Fazio and Monti (2011) highlighted as well that *M. giganteus* allowed a drastic decrease in GHG emissions compared to annual crops. On the opposite, these authors showed that the crop performed as well or even slightly worse than other perennial crops such as willow (Styles & Jones 2007, Saint Clair *et al.* 2008, Hillier *et al.* 2009), switchgrass or giant reed (Fazio & Monti 2011). In all these studies except Saint Clair *et al.* (2008), *M. giganteus* was N-fertilized every year while it was N-fertilized every three years in our study. On LC soil, the first category also contained nitrate losses and *M. giganteus* was again widely better than the other crops. On CC soil, alfalfa was associated with lower nitrate losses than *M. giganteus*, whatever the yield scenario involved. Results on nitrate losses must however be regarded with caution, since the methodology relied on a nitrogen balance for the annual crops while it relied on the estimation of the soil mineral content at the beginning of winter for alfalfa and *M. giganteus*. Besides, the scarcity of data on CC soil added to the lack of knowledge on the long-term evolution of nitrate losses under low yielding *M. giganteus* makes the results even more uncertain on that soil. TFI was another field assessment where ranking did not rely on *M. giganteus* yield scenario. Regarding TFI, *M. giganteus* outperformed again any other crop but alfalfa since this crop required almost no pesticide as well.

Assessment fields where ranking among crops relied on *M. giganteus* yield scenario included energy costs, energy efficiency and snM. Alfalfa stems displayed lower energy costs and higher energy efficiency per ton than the lowest yielding *M. giganteus* on both soils. On LC soil, any other crop was characterized by similar or even slightly higher snM than the lowest yielding *M. giganteus*. On CC soil, dedicated winter triticale and alfalfa stem snM got closer *M. giganteus* snM estimated with the highest yield scenario for that soil. Styles and Jones (2008) found that *M. giganteus* provided gross margins higher than winter wheat even with their lowest yield assumption where mean yield was equal to 8.2 t DM ha^{-1} y^{-1}. Their assumption on *M. giganteus* was however 40% higher than ours. With a price about 25% lower than ours and a mean yield close to our intermediate yield scenario (14 t DM ha^{-1} y^{-1}), Krasuska and Rosenqvist (2011) found that *M. giganteus* was not profitable, neither was dedicated triticale under the same price assumption and yield and management similar to ours. According to the price assumptions, winter wheat was either even less profitable than

M. giganteus or profitable. In Styles and Jones (2008) and Krasuska and Rosenqvist (2011) studies, *M. giganteus* was N-fertilized every year while it was N-fertilized every three years in our study.

Among the other energy feedstock, alfalfa stems turned out to be very interesting. Dedicated crops also earned good results on an economical basis but did not perform as well as alfalfa stems on an environment and GHG emission basis. Straw was characterized by the worse results, although triticale straw performed better than wheat straw and got close results to dedicated triticale. This is explained by its higher straw yield and lower input requirement compared to wheat. Ravn Jorgensen *et al.* (2007) had also shown that triticale and rye, thanks to their higher whole plant yield, were more interesting than wheat. However, compared with first generation crops, the use of straw as an energy feedstock allowed a strong decrease in GHG emissions. Furthermore, exported straw of a cereal cultivated after alfalfa improved the results. This could be generalized to other legume regarding the reduction in N rate (but probably in a lower extent) and the positive preceding effect regarding yield. On the opposite, the positive preceding effect regarding the reduction of weeding is strictly related to alfalfa. Hallam *et al.* (2001) compared alfalfa with perennial crops such as reed canary grass (*Phalaris arundinacea L.*) and switchgrass, as well as with annual crops such as sorghum and maize. On a cost based comparison, alfalfa performed worse than both perennial and annual crops. Alfalfa was cut two or three times a year but was mowed which required three harvest operations (the mow, the baling and the bale load) compared to one in our study.

4.3. Comparison of the cropping systems

Before discussing comparisons between cropping systems, we must first of all emphasize that the objectives set at the beginning of the workshop were reached: compared to CS1, GHG emissions were reduced by 50 to 75%as a function of soil type and energy cropping system, TFI were reduced by 70 to 95% and nitrate losses by 55 to 80%. In the meanwhile, food crop yield were not reduced by more than on average 15%. The design workshop was then on the whole successful. However, we shall notice that the poor results of CC2 compared to LC2 were related to the low semi-net margin associated to winter barley (80 € ha^{-1}) and sunflower (20 € ha^{-1}) due to low yields (respectively 66 and 52% of potential yields): this result questioned therefore the management described by the experts, not to say perhaps the inclusion of those crops in integrated cropping systems for CC soil.

Comparison at the cropping system scale depended (i) on the assumptions made for *M. giganteus* yield and (ii) on the weight of *M. giganteus* in the cropping system. With moderate or high yields, *M. giganteus* based cropping system outperformed the other cropping systems, except regarding the capacity to produce food. With low yields, on both soils, *M. giganteus* based cropping system still got better results as far as GHG emission and energy production were concerned. On CC soil, results regarding energy production would be nevertheless different if alfalfa was the only energy feedstock included in CC4 (cf 4.2). Comparison regarding nitrate losses differed according to soil types, while comparison regarding pesticide pressure differed according to the weight of *M. giganteus* and alfalfa in the cropping systems. With low yields, other CS got similar or even better snM than *M. giganteus*, especially on CC soil. On this soil, it would have been very valuable to base the yield scenarios on more commercial yield data to be able to judge if *M. giganteus* crop is really suitable for such a soil.

Our study was based on the hypothesis that an assessment of energy feedstock at the cropping system scale was necessary because (i) food crops could benefit from the introduction of energy crops in the crop sequence and (ii) energy resource assessment could be affected since preceding effects modify yields, crop management and as a consequence the derived indicators. We showed indeed that the introduction of alfalfa as a multiple product crop improved cropping system assessment results. We also highlighted that the assessment results of an energy feedstock such as straw wheat differed according to the preceding crop. Furthermore, when considering a supply area or a watershed, the risk of environmental impacts is related to all the crops cultivated in the cropping systems of the area and not only to the energy feedstock, which also makes the assessment at the cropping system scale necessary.

4.4. Main uncertainties

Working with different yield assumptions for *M. giganteus* improved a lot the discussion of the crop interests, especially because these assumptions, based on fields network measurements were related to soil, field environment and field management. We also integrated long-term yield evolution using the findings of **Chapter 4**. We assumed that fertilizing the crop with N every three years and with P and K every six years would not cause yields to decline with a higher rate than the average one of **Chapter 4**. However, in all assessment studies cited here except Saint Clair *et al.* (2007), *M. giganteus* was N-P-K fertilized every year. We hypothesized that *M. giganteus* had no preceding effect in terms of yield of the following crops, which need to be confirmed. Our study benefited also from the results regarding nitrate losses as a function of crop age and soil type (**Chapter 3**). However, knowledge on long-term nitrate losses evolution was not available, which is particularly critical when yields are low. Besides, knowledge on nitrate losses and GHG emissions occurring after the crop destruction was lacking as well. We made assumptions to take N_2O emissions into account but they involved only the destruction year while nitrogen contained in rhizomes will increase the soil nitrogen likely to contribute to leaching or soil N_2O emissions gradually. In the meanwhile, part of this nitrogen could be absorbed by the following crops.

Based on the high C/N of *M. giganteus* rhizomes (Amougou *et al.*, 2010), we assumed that the crop destruction would not modify nitrate leaching during winters of the following years. Further research is however needed on these aspects.

Soil N_2O emissions estimation in general could be more precise if information on soil type, climate and following crops were taken into account. Soil N_2O emissions also increase when soil carbon content, *i.e.* organic matter content, decreases (IPCC, 2006). Soil carbon evolution was not included in our study but straw exportation was however design to prevent any loss in organic matter. Based on the information available in the literature, unlike annual crop based cropping systems, cropping systems based on *M. giganteus* should induce an increase in soil carbon stocks (Himken *et al.*, 1997; Neukirchen *et al.*, 1999; Hansen *et al.*, 2004; Hillier *et al.*, 2009). However, we mentioned in **Chapter 2** that *M. giganteus* was frequently planting on fields that were set-aside and can therefore be assimilated to grasslands on a carbon stock point of view. The change in carbon stock when *M. giganteus* replaces grassland is considered to be null (Saint Clair *et al.*, 2008; Hillier *et al.*, 2009). However, when GHG emissions related to the crop production and GHG savings related to fuel displacement is taken into account, *M. giganteus* still displays a better GHG balance than annual crops such as winter wheat or oilseed rape (Saint Clair *et al.*, 2008; Hillier *et al.*, 2009).

GHG emissions when expressed by ton to compare energy feedstock depend on crop yields. In this study, we assumed yields to be a good indicator of energy yields and used therefore different indicators such as GHG emissions, energy efficiency and semi-net margin expressed by ton to compare energy feedstock. Processes to transform energy feedstock into second generation bioethanol are however mainly still experimental and differences among crops could appear, especially regarding the energy and the inputs required for pre-treatment. Furthermore, differences in yield sensitivity regarding climate change could change the comparison results between crops. These differences could also have a strong impact on the relative crop profitability. Regarding economical results, as mentioned by Krasuska and Rosenqvist (2011), the prices of biomass as well as the prices of non-energy crop are key factors to determine the profitability and competitiveness of energy crops. Given the uncertainty regarding these prices, *M. giganteus* benefit from low costs, especially fertilization costs: the crop is therefore rather independent from changes in the agricultural input prices. However, the high establishment costs along with the long payback period could be a barrier to the crop development (Styles & Jones, 2008; Bocquého & Jacquet, 2010).

Apart from *M. giganteus*, alfalfa stems emerge from our study as a very promising bioenergy feedstock. Alfalfa is yet not commonly included in assessments comparing energy feedstock. Hallam *et al.* (2001) compared dedicated alfalfa with several crops (see 4.2) and found that alfalfa was disadvantaged by its shorter life span compared to perennial crops and in general by the multiple cuttings per year. Lamb *et al.* (2007) studied the use of alfalfa stems to produce bioethanol and showed that alfalfa would benefit from a biomass management system based on a reduced population density in order to increase stem yield and on a two-cut harvest regime in order to reduce harvest costs and to improve the crop longevity. Gonzalez-Garcia *et al.* (2010a) compared conventional gasoline with bioethanol produced from alfalfa stems using the LCA methodology and showed that the latest leads to reduce the global warming potential while environmental impacts such as those related to acidification or eutrophication increased. Gonzalez-Garcia *et al.* (2010b) also compared the use of alfalfa stems with the use of other crops such as poplar, flax shives or hemp hurds (i.e. the non-fiber part of the stems) and ethiopan mustard and showed that the latest was the most interesting feedstock regarding GHG emissions and eutrophication. Neither of these studies compared alfalfa stems with the energy feedstock studied here nor gave details either on the process required to separate leaves and stems.

4.5. Assessing more energy feedstock?

In this study, we compared cropping systems based on *M. giganteus* with cropping systems including various energy feedstocks. Other energy feedstocks of interest could not be included in the assessment because they were not parameterized in PerSyst. On CC soil, switchgrass could be an interesting crop because it is said to be more drought resistant than *M. giganteus* providing that the tricky implantation of the crop is possible on a stony soil. On LC soil, willow would probably perform well, but willow yield are generally lower *M. giganteus* resulting in better assessment results per ton for the latest (Styles & Jones, 2007; 2008). The situation should be different on wet soils where willow would be more suitable (Styles & Jones, 2007; 2008). Except the issue of drying, sorghum (sweet sorghum or fiber sorghum) was assessed as a very interesting crop by Fazio and Monti (2011) and Hallam *et al.* (2001): these authors underlined the fact that sorghum could compete with perennial crops such as switchgrass, big bluestern (*Andropogon gerardii*) and cynara (*Cynara cardunculus L.*). Based on our expert panel, sorghum would be suitable for LC soil and could be cultivated as second crop after dedicated triticale. Intercrops of alfalfa and sorghum (Hallam *et al.* 2001) maize and *Lolium perenne* (Boehmel *et al.* 2008) or wheat and clover-grass (with straw grain dedicated to food production) (Thomsen & Haugaard-Nielsen, 2008) were also mentioned as feedstock of interest.

5. Conclusion

Our study aimed at comparing *M. giganteus* with other potential biofuel agricultural feedstock (i) using multicriteria cropping system assessment as a methodological framework, and (ii) using data representative of production-scale fields managed commercially. Two categories of energy oriented cropping systems were designed for two soil types of Burgundy based on expert knowledge: cropping systems including *M. giganteus*, and cropping systems based on annual and/or pluri-annual dedicated or multiple product crops. Energy cropping systems were compared to two reference cropping systems which did not include energy feedstock: one corresponding to the most widespread practices in the studied region (based on rapeseed – wheat – barley) and one based on integrated management rules. Cropping system multicriteria assessment results were sensitive to (i) *M. giganteus* yield and (ii) *M. giganteus* weight in the cropping system. Regarding environmental performances (nitrate leaching, pesticide use, greenhouse gas emissions) as well as energy performances, cropping systems including *M. giganteus* were on the whole better than those including other energy feedstock. On the opposite, economic results were very sensitive to *M. giganteus* yields. Both categories of energy cropping systems displayed better environmental performances than the conventional cropping system based on rapeseed – wheat – barley. They also performed better than the integrated cropping systems thanks to the insertion of multi-annual (alfalfa) or perennial crops (*M. giganteus*) in the cropping sequence. Economic results were again more variable depending on soil type and yield level of the different crops. Among other candidate feedstock, alfalfa, whose stems can be used to produce second-generation bioethanol, displayed several advantages. It was characterized by low environmental impact while maintaining interesting yields on soils where water availability is reduced. Including alfalfa in cropping systems also had positive impacts on the assessment results of other candidate feedstock such as cereal straws thanks to the preceding and cumulative effects associated to the crop. Interest of cereal straws or whole plants (corn silage, triticale) as energy crops depended on their yield levels on each soil types compared to those of *M. giganteus* and alfalfa.

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Chapitre 6.

Discussion générale

Ce travail repose sur deux originalités principales : (i) l'étude de *M. giganteus* en parcelles agricoles, et (ii) la comparaison de systèmes de culture intégrant différentes ressources candidates à la production de bioénergie (dont *M. giganteus)*, sur la base de leur évaluation *ex ante*. Dans un premier temps, nous discuterons des principaux apports de connaissance permis par le suivi de parcelles agricoles de *M. giganteus*. Nous reviendrons ensuite sur les conséquences de l'introduction de *M. giganteus* ou de d'autres ressources candidates dans les systèmes de culture. Un retour sur les grands choix méthodologiques sous-jacents à ce travail constituera la suite de la discussion. Enfin, des perspectives relatives aux changements d'échelle seront présentées.

1. Cultiver *M. giganteus* en parcelles agricoles

1.1. Caractérisation et explication de la variabilité des performances de *M. giganteus* en parcelles agricoles

Les résultats obtenus en parcelles agricoles, qu'ils concernent le rendement de *M. giganteus* ou le risque de lessivage de nitrates pendant l'hiver, sont cohérents avec ceux obtenus en parcelles expérimentales si l'on considère les valeurs moyennes obtenues sur l'ensemble du réseau de parcelles agricoles. En revanche, le suivi de parcelles agricoles a permis de mettre en évidence la grande variabilité des rendements comme des pertes de nitrates. Le suivi de parcelles agricoles a de plus permis d'identifier les principales sources de variabilité et de montrer qu'elles ont un impact différent lorsqu'il s'agit des rendements ou du lessivage de nitrates.

En termes de rendements, nous avons montré que la densité de tiges mise en place pendant la première année de culture est la variable qui a le plus d'influence : la réussite de la plantation est donc déterminante. Nous avons également montré que cette plantation est plus risquée (i) en sol peu profond et/ou caillouteux et (ii) en sols humides avec précédent jachère. Le type de sol a donc été identifié comme une source de variabilité. Toutefois, alors que dans la littérature, l'influence du type de sol est reliée à sa disponibilité en eau (Heaton *et al.*, 2004; Richter *et al.*, 2008; Hastings *et al.*, 2009), le type de sol intervient ici avant tout en interaction avec l'historique de la parcelle et la conduite de la culture: les parcelles plantées sur des sols humides avec comme précédent une jachère longue durée présentent un risque d'échec de la plantation plus élevé (apprécié par la densité de tiges par m^2 à la fin de l'année d'implantation). Le dispositif d'analyse des rendements (**Chapitre 2**) n'a pas réellement permis d'analyser l'influence de la disponibilité en eau: le nombre de parcelles où de faibles réserves utiles ont été estimées était très réduit et certaines de ces parcelles bénéficient de plus de la présence d'une nappe phréatique proche. Lorsque le dispositif est élargi des parcelles suivies dans le cadre du **Chapitre 2** (20 parcelles où le rendement « placette » a été estimé) à l'ensemble des parcelles suivies (38 parcelles où le reliquat d'azote minéral dans le sol a été estimé) (**Chapitre 3**), l'influence de la disponibilité en eau est plus marquée. Cet élargissement permet en effet l'ajout des huit parcelles plantées dans la zone de Baigneux-les-Juifs[15]. Sur deux d'entre elles, localisées en sol argilo-calcaire superficiel, la plantation a échoué suite au dessèchement des rhizomes. Sur les six parcelles restantes, trois parcelles plantées sur des sols argilo-calcaires superficiels ou moyens et âgées de deux et trois ans n'ont pas encore été récoltées, faute de biomasse suffisante. Seules deux parcelles plantées sur des sols argilo-calcaires moyens font l'objet de récolte[16] et présentent de faibles rendements « machine » (environ 4 t MS ha^{-1} en première récolte, 8 t en deuxième). Au-delà de la disponibilité en eau, ces parcelles subissent probablement également l'influence de températures moyennes moins élevées sur le plateau calcaire Bourguignon.

L'analyse des pertes de nitrates concerne elle l'ensemble des 38 parcelles du réseau. Ces pertes sont en moyenne faibles et diminuent quand l'âge de la culture augmente. L'influence du type de sol est cette fois extrêmement forte. Sur les sols profonds, l'influence du type de sol semble supérieure à celle des niveaux de rendement de la culture (et donc des prélèvements d'azote et d'eau associés ; ces derniers jouant sur le drainage). Les parcelles plantées sur des limons battants, sols profonds caractérisés par de faibles taux de minéralisation potentielle de l'azote (**Chapitre 3**) présentent ainsi un risque de lessivage faible quel que soit le niveau de rendement de la culture (**Annexe 4**). En revanche, les parcelles de *M. giganteus* plantées sur des sols argileux présentent un risque de lessivage plus élevé, y compris pour de bons niveaux de rendement (**Annexe 4**). Cette analyse est délicate à mener pour les sols plus superficiels en raison du nombre insuffisant de parcelles présentant des niveaux de rendement moyens ou élevés sur ces sols.

Comparée aux dispositifs expérimentaux, l'analyse en parcelles agricoles a permis d'identifier des sources de variabilité supplémentaires. Le choix des parcelles où *M. giganteus* est cultivé joue ainsi un rôle central. Comme nous l'avons mentionné ci-dessus, les parcelles plantées sur des sols humides avec un précédent jachère présente un risque d'échec de la plantation plus élevé. Il s'agit d'ailleurs probablement d'une auto-corrélation : ces parcelles avaient vraisemblablement été mises en jachère par les agriculteurs car elles étaient difficiles à travailler, par exemple en raison d'excès d'eau à certaines périodes de l'année. D'autre part, le **Chapitre 2** a également mis en évidence que la culture de *M. giganteus* sur des parcelles de forme particulière (petite taille, nombre d'angles) augmente les risques de pertes à la récolte. Bien que nous ne l'ayons pas mis formellement en évidence, le désherbage des parcelles en première année joue vraisemblablement un rôle clef. Toutefois, hormis le désherbage et

[15] En raison de contraintes matérielles et du nombre très limité de parcelles récoltées dans cette zone, nous avons choisi de ne pas inclure ces parcelles dans le dispositif étudié au Chapitre 2.

[16] La dernière parcelle des huit évoquées ici se situe à l'écart des autres sur un sol limono-argileux profond.

contrairement aux cultures annuelles classiques, les sources de variabilité supplémentaires identifiées en parcelles agricoles sont peu liées directement à la conduite de la culture, qui est très peu variable entre parcelles. Cela dit, l'impact de l'interaction sol – précédent, qui rend la plantation plus délicate sur certaines parcelles, appellerait à une gestion différente de ces parcelles. Si l'analyse en parcelles agricoles confirme que la plantation est l'étape déterminante de la réussite de la culture, ce n'est toutefois pas tant la levée des rhizomes qui a été déterminante sur le réseau de parcelles étudié ici mais la multiplication du nombre de tiges par rhizome levé. Cette observation tend à montrer que le tri des rhizomes effectué par Bourgogne Pellets avant la plantation a globalement permis de contrôler la qualité des rhizomes, élément primordial pour réussir l'implantation (RMT BIOMASSE, 2012b). La division mécanique des rhizomes à l'issue de la première récolte (appelée « remise à zéro de la parcelle) a été utilisée sur deux parcelles pour palier une densité de peuplement trop faible et trop irrégulière : les récoltes des années à venir permettront de juger de l'efficacité de cette technique. Notons que les coûts d'implantation représentent une part importante des coûts de production de *M. giganteus* et pourraient constituer une barrière au développement de cette culture (Styles *et al.,* 2008) : cette barrière sera d'autant plus élevée que le risque d'obtenir une mauvaise implantation est lui aussi élevé. Planter la culture à partir de graines et non de rhizomes permettrait de réduire aussi bien les coûts économiques de plantation que les coûts énergétiques et au-delà les émissions de gaz à effet de serre (Hastings *et al.,* 2009). Cette option est à l'étude et sera prochainement explorée dans le cadre du projet « Biomasse pour le futur ».

1.2. Cultiver *M. giganteus* sur des terres marginales ?

Une des solutions proposées pour limiter la concurrence entre productions alimentaires et non alimentaires est de concentrer les productions non alimentaires sur des terres marginales. La notion de terres marginales est cependant fréquemment peu ou non définie (Batidzirai *et al.,* 2012), bien qu'elle implique en général la notion de « faible productivité ». Dans un rapport pour la FAO dédié aux terres marginales [17], le Consultative Group on International Agricultural Research (CGIAR) rappelle que la notion de terres marginales est relative puisque (i) y compris au sein des usages agricoles, un sol peut être considéré comme marginal pour un usage (exemple : cultures annuelles) mais tout à fait adéquat pour un autre (exemple : prairies), et (ii) le caractère marginal peut faire référence à des contraintes biophysiques (sol peu drainant, sol séchant, parcelle en pente, etc.), mais aussi à des contraintes socio-économiques (absence d'accès au marché, statut foncier de la parcelle, accès à la parcelle difficile, ratio « input / output » défavorable, etc.). Face à la question spécifique de la production de bioénergie sur des terres marginales, Wicke (2011) distingue (i) les terres

[17] http://www.fao.org/Wairdocs/TAC/X5784E/x5784e00.htm#Contents; Chapitre II

dégradées, définies comme des terres caractérisées par une perte sur le long terme de fonctions ou de services écosystémiques que le système ne pourra pas retrouver seul et (ii) les terres marginales où la production de cultures alimentaires avec une efficience économique correcte est délicate en raison de caractéristiques de la parcelle ou en raison de problèmes techniques. A l'échelle de l'exploitation agricole, selon Bocquého (2012), une parcelle est dite marginale si elle est significativement moins rentable que le reste des parcelles de l'exploitation à cause de coûts de production élevés (y compris en travail), de rendements faibles ou d'autres contraintes. Sur la base de cette définition, et l'aide de 111 enquêtes réalisées en 2010 dans la zone d'Aiserey et de Baigneux-les-Juifs[18], Bocquého (2012) montre que 56% des parcelles de *M. giganteus* enquêtées ont été plantées sur des parcelles qualifiées de marginales par l'agriculteur, en raison principalement de la qualité du sol (granulométrie, cailloux, profondeur, hydromorphie, caractère séchant) (36%), de l'éloignement au siège d'exploitation (30%), de la taille de la parcelle (21%) ou encore d'une forme irrégulière (16%)[19]. Les autres raisons évoquées sont la proximité avec des bois ou des habitations ou encore une localisation enclavée. Dans notre dispositif d'étude en parcelles agricoles, un agriculteur a également qualifié de parcelle marginale une parcelle localisée dans une zone à intérêt environnemental (ex : zone Natura 2000). D'après Bocquého (2012), ces raisons sont susceptibles de diminuer la rentabilité des parcelles, mais d'augmenter les performances de *M. giganteus* en termes de durabilité. Ainsi, une parcelle où le potentiel de rendement est faible représente un volume de production alimentaire perdu faible. De même, planter *M. giganteus* sur une parcelle éloignée du siège de l'exploitation permet d'éviter une quantité plus importante d'émissions de gaz à effet de serre, en particulier lorsque la production remplacée est très exigeante en opérations culturales (et donc en déplacements associés).

Sur les quarante parcelles suivies ici, les agriculteurs évoquent une qualité médiocre du sol pour 30% des parcelles. Le caractère enclavé est cité pour 30% des parcelles mais semble faire référence à la fois à la taille ou à la forme des parcelles, ainsi qu'à leur environnement (accès, proximité d'une forêt). La difficulté à travailler la parcelle (en raison de sa forme, de son environnement proche ou du sol) et l'éloignement sont évoqués dans 20 et 12,5% des cas. En se fondant sur la définition de Bocquého (2012) et sur les résultats obtenus aux **Chapitres 2 et 3**, il semble pertinent de distinguer (i) les parcelles qualifiées de marginales car leur exploitation est contraignante et (ii) celles qualifiées de marginales car le potentiel de production y est faible. Lorsqu'il s'agit du potentiel de production (sols argilo-calcaires superficiels ou moyens, sols alluviaux superficiels et caillouteux), les **Chapitres 2 et 3** montrent que ces parcelles restent marginales pour la culture de *M. giganteus* (au sens où les rendements obtenus sont limités) et que le risque de lessivage de nitrates y est élevé. Lorsque

[18] Une partie des agriculteurs du réseau de parcelles de *M. giganteus* mobilisé dans les **Chapitres 2 et 3** font également partis de ce dispositif.

[19] Bocquého (2012) précise qu'une même parcelle est le plus souvent marginale pour plusieurs raisons à la fois.

c'est l'exploitation de la parcelle qui est contraignante, le **Chapitre 2** montre que la production de *M. giganteus* avec des rendements moyens et hauts est possible mais que certaines parcelles (parcelles éloignées ou parcelles à sol humide avec précédent jachère) présentent un risque de mauvaise implantation plus élevée : la conduite devrait donc y être adaptée. Des caractéristiques comme la forme des parcelles entrainent également un risque de pertes à la récolte plus importantes. Le risque de lessivage n'est en revanche pas influencé par de telles caractéristiques. Ces conclusions permettent de nuancer celles de Bocquého (2012) citées ci-dessus concernant l'augmentation de la durabilité de la production de *M. giganteus* sur des parcelles marginales : cette augmentation est possible sous réserve que les rendements de la culture soient suffisants.

1.3. *M. giganteus* : la culture candidate à la production de bioénergie la plus prometteuse ?

De nombreux travaux reposant sur des données expérimentales ou des modèles présentent *M. giganteus* comme une des cultures, voire la culture, la plus intéressante pour produire des bioénergies (Heaton *et al.*, 2008b, 2010; Hastings *et al.*, 2009; Dohleman & Long, 2009). L'analyse des performances de *M. giganteus* en parcelles agricoles (**Chapitre 2 et 3**) couplée à la comparaison de systèmes de culture (**Chapitre 4**) menée dans ce travail permet de nuancer cette affirmation.

En sols profonds, à l'exception de parcelles où l'implantation pose problème, *M. giganteus* apparaît effectivement comme une culture très performante. Il convient alors de se demander si le nombre de parcelles où l'implantation n'est pas satisfaisante diminuera grâce à l'expérience acquise sur la culture. Notons à ce sujet que le conseil effectué auprès des agriculteurs était pourtant très clair sur la nécessité de bien désherber pendant la première année (Béjot, comm. pers.). Les échecs observés lors des plantations 2009 n'ont d'autre part pas empêché l'existence de difficultés similaires lors des plantations 2010. Il semble que *M. giganteus* ait souffert de son image de culture « où il n'y a rien à faire ». En sols superficiels, la production de *M. giganteus* paraît périlleuse puisque (i) le risque d'échec de la plantation est très élevée (deux parcelles sur trois dans notre dispositif ; la troisième n'ayant toujours pas été récolté faute de biomasse en quantité suffisante). En sol moyennement profond (sol CC), le **Chapitre 5**montre que cette production est intéressante d'un point de vue réduction des émissions de gaz à effet de serre. Elle est également associée à des impacts environnementaux locaux inférieurs à ceux des cultures annuelles. Toutefois, l'utilisation de tiges de luzerne paraît tout autant intéressante de ce point de vue. Enfin, d'un point de vue économique, *M. giganteus* ne se distingue pas des autres cultures étudiées dans le **Chapitre 5** sur ce sol.

Le **Chapitre 5** montre que certains indicateurs utilisés pour évaluer *M. giganteus* (à l'échelle du système de culture comme de la culture) sont très sensibles au scénario de rendement retenu : c'est particulièrement le cas de l'efficience énergétique et de la marge semi-nette. Styles *et al.* (2008) avaient déjà comparé *M. giganteus* avec d'autres ressources candidates à la production de bioénergie en utilisant plusieurs hypothèses de rendement. Toutefois, les scénarios de rendement utilisés dans le **Chapitre 5** présentent l'avantage de s'appuyer sur des données recueillies en conditions agricoles et d'être contextualisés puisqu'ils sont reliés à des caractéristiques de sol, ainsi qu'à des interactions entre sol, caractéristiques de la parcelle et conduite de la culture. Ces scénarios mériteraient cependant d'être affinés en intégrant la variabilité interannuelle des rendements : le **Chapitre 5** montre en effet que cette dernière est variable entre sites mais peut être élevée. Ce Chapitre montre aussi que l'intensité du déclin est très variable entre sites : les scénarios de rendement pourraient tenir compte de la variabilité du taux de déclin, ce qui pourrait conduire à envisager des durées de vie différentes pour la culture si le déclin est particulièrement fort. Toutefois, le **Chapitre 5** n'a pas permis de relier cette variabilité à des conditions de pédo-climat ou de conduite, ce qui serait pourtant nécessaire afin de conserver des scénarios contextualisés.

La comparaison effectuée ici repose sur un seul clone de Miscanthus, *Miscanthus x giganteus*, qui est considéré comme le plus productif (Zub & Brancourt-Hulmel, 2010b). D'autres genres de Miscanthus sont cependant connus pour être plus résistants au froid ou à la sécheresse (Zub & Brancourt-Hulmel, 2010b) : lors d'un essai européen, un hybride de *M. sinensis* a ainsi montré des traits de résistance au froid et à la sécheresse intéressants (Clifton-Brown *et al.*, 2001). Sur cette base, Hastings *et al.* (2009) montrent à l'aide du modèle MISCANFOR l'intérêt d'un nouvel hybride les caractéristiques de *M. giganteus*, *i.e.* un rendement élevé, et celle de *M. sinensis*, *i.e*. la résistance au froid et à la sécheresse, dans un contexte de changement climatique, alors que la production d'énergie et le potentiel de réduction des émissions de gaz à effet de serre associé à la production de *M. giganteus* pourrait diminuer de 80% d'ici 2080 (avec le scénario A2 du GIEC). Affiner la comparaison entre *M. giganteus* et d'autres cultures candidates impliquerait donc de quantifier le potentiel d'amélioration génétique de la culture.

2. Des cultures énergétiques insérées dans des systèmes de culture

Une hypothèse forte de ce travail est que l'évaluation des intérêts de différentes cultures candidates à la production de biocarburants (et de bioénergie en général) mérite d'être effectuée non seulement à l'échelle de la culture mais également à celle du système de culture. Nous allons revenir sur cette hypothèse pour la culture de *M. giganteus* puis pour les autres ressources étudiées dans ce mémoire.

2.1. *Miscanthus*x *giganteus*et système de culture

L'insertion de *M. giganteus* dans un système de culture est délicate à raisonner compte-tenu (i) de la durée de vie de la culture, de très loin supérieure à la durée de raisonnement des systèmes de culture les plus répandus actuellement et (ii) du manque de connaissance en termes d'effets précédents et cumulatifs associés à la culture. En l'état actuel des connaissances, le **Chapitre 5** montre que les résultats de l'évaluation de systèmes de culture comprenant *M. giganteus* dépendent de la part occupée par la culture dans le système de culture. L'impact de l'insertion de cette culture dans un système de culture est directement relié à sa durée de vie : plus celle-ci est longue, plus les valeurs moyennes des indicateurs sont faibles. L'impact en termes d'effets précédents ou cumulatifs dans les systèmes de culture conçus lors de l'atelier de conception de système de culture mené en Bourgogne n'a été décrit par les experts que pour le désherbage de la culture suivante en sol limono-argilo profond. Pour le sol argilo-calcaire moyen, l'impact agronomique de *M. giganteus* a été envisagé en termes d' « effet barrière » (contre le vent ou les maladies) grâce à l'organisation en bande adoptée. L'insertion de *M. giganteus* dans un système de culture a été en fait peu raisonnée par les experts en termes d'interaction ; l'insertion de *M. giganteus* a par contre été vue comme un levier permettant d'obtenir un système de culture à très faible impact environnemental grâce aux faibles impacts moyens qui le caractérisent. Dans le cas du sol limono-argileux profond (LC 3), la culture a été utilisée par les experts comme le pilier d'un système de culture à faibles impacts sur la qualité de l'eau. Dans cette perspective, les risques d'impact environnementaux (lessivage de nitrates, utilisation accrue d'herbicides), plus élevés en début et en fin de culture, sont masqués dans les résultats d'évaluation par l'utilisation de valeurs moyennes mais ne sont pas à négliger. L'insertion de *M. giganteus* dans le système de culture conçu sur le sol argilo-calcaire moyen (CC 3) a elle pour vocation de réduire les émissions de gaz à effet de serre à l'échelle de la parcelle tout en conservant une production alimentaire suffisante sur cette même parcelle. Ce raisonnement est cohérent avec les objectifs fixés lors de l'atelier de conception de systèmes de culture. Toutefois, mis à part de possibles effets « barrière » liés au système en bande, des résultats similaires pourraient aussi être obtenus en raisonnant à l'échelle du territoire, ce qui pourrait permettre de plus de valoriser la diversité des milieux existant à cette échelle.

2.2. Cultures énergétiques et système de culture

Les autres cultures candidates à la production de biocarburants étudiées ici sont la luzerne (avec utilisation uniquement des tiges), les pailles de blé et de triticale, ainsi que le maïs et le triticale en plante entière. L'insertion de ces cultures dans un système de culture doit se raisonner de deux manières : effet des cultures à vocation énergétique (ou mixte) sur les autres cultures de la succession et inversement. Parmi les cultures citées ci-dessus, les experts de l'atelier de conception de système de culture (**Chapitre 5**) n'ont fait état d'effets précédents (voire cumulatifs) que pour la luzerne. Ces effets concernent le blé de luzerne, aussi bien dans sa vocation alimentaire que dans sa vocation énergétique. Le raisonnement des systèmes des systèmes de culture énergétiques repose sinon sur l'insertion du pois (effet précédent sur le colza souvent mis en avant) et de cultures de printemps. A l'exception de la luzerne, le débouché « biocarburant » ne paraît donc pas être un levier important de diversification des systèmes de culture. Ceci est toutefois à nuancer car d'autres ressources n'ont pas pu être envisagées, faute de connaissance. Zegada-Lizarazu et Monti (2011) citent ainsi l'intérêt du sorgho (qui pourrait être utilisé en plante entière ou en co-produit pour produire du bioéthanol), du tournesol (co-produit), du lin (plante entière ou résidus après extraction des fibres), du chanvre (plante entière ou résidus après extraction des fibres) ou encore de la moutarde éthiopienne. Zegada-Lizarazu et Monti (2011) mentionnent l'intérêt de ces espèces pour diversifier les systèmes de culture, contrôler certains ravageurs (chanvre), utiliser efficacement les ressources du sol (sorgho, tournesol, moutarde éthiopienne) ou améliorer la structure du sol (chanvre, moutarde éthiopienne). Toutefois, ces auteurs mentionnent aussi que la connaissance des effets rotationnels de ces cultures est souvent limitée. Hallam *et al.* (2001) ainsi que Thomsen et Haugaard-Nielsen (2008) soulignent également l'intérêt des associations d'espèces. En France, les cultures intermédiaires à valorisation énergétique (CIVE) font également l'objet de travaux (projet OPTABIOM). Zegada-Lizarazu et Monti (2011) discutent de l'intérêt de concevoir des systèmes de culture composés uniquement de cultures à vocation énergétique : de tels systèmes auraient pour avantage de réduire la taille des bassins d'approvisionnement mais leur intérêt paraît, aux yeux des auteurs, limités en raison du faible nombre d'espèces à haut potentiel de production.

3. Conception et évaluation de systèmes de culture contenant des cultures candidates à la production de bioénergie

3.1. Du diagnostic agro-environnemental à l'évaluation de systèmes de culture : le couplage modèle-mesure

L'évaluation comparée de systèmes de culture à laquelle est consacré le **Chapitre 5** repose sur l'utilisation du modèle PerSyst (Guichard *et al.*, submitted, 2010, Annexe 5). La principale originalité de ce modèle est de permettre l'estimation du rendement des cultures d'un système de culture en fonction du sol, du climat, des cultures de la succession et des conduites, en combinant des connaissances expertes et des modèles simples. L'introduction récente de *M. giganteus* dans la région d'étude ainsi que son caractère pérenne rendait impossible la mise en place d'une démarche d'élicitation des connaissances expertes telle qu'elle est réalisée dans PerSyst. La démarche adoptée pour estimer les rendements de *M. giganteus,* ainsi d'ailleurs que le lessivage de nitrates pendant l'hiver, n'est toutefois pas si éloignée de la démarche mise en œuvre dans PerSyst. Elle repose en effet sur le couplage entre des données acquises en parcelles agricoles et des modèles.

Pour le rendement, le modèle statistique à effets aléatoires mis au point au cours du **Chapitre 4** a permis de simuler parcelle par parcelle l'évolution à long-terme des rendements à partir des données collectées pour les deux premières récoltes. Ce type de modèle a l'avantage d'être ajustable localement même quand seulement quelques données sont disponibles. Il permet ainsi de réaliser des prédictions sans connaître les caractéristiques pédo-climatiques d'un site. L'intérêt de ce type de démarche a été souligné par Philibert (2012) dans le cadre de la prédiction des émissions de N_2O par les sols agricoles. Plus classiquement, le modèle LIXIM (Mary *et al.*, 1999) utilisé dans le **Chapitre 3** a permis de simuler le lessivage hivernal de nitrates à partir des données sol collectées en entrée et sortie d'hiver.

L'analyse de données recueillies en parcelles agricoles a permis dans les deux cas de mener une démarche de diagnostic pour caractériser et comprendre la variabilité observée. Dans un deuxième temps, le couplage avec des modèles a permis de fournir des données mobilisables lors du travail d'évaluation *ex ante* de système de culture. L'ensemble de la démarche a produit une évaluation ex ante de système de culture « contextualisée » dont les résultats peuvent toutefois être discutés au-delà des sols et des systèmes de culture étudiés. C'est en particulier le travail de diagnostic et l'explicitation du raisonnement des experts lors de l'atelier de conception de systèmes de culture qui permettent d'extrapoler les résultats au-delà de la région étudiée.

Si la variabilité des rendements associée au type de sol et au système de culture a bien été intégrée, la variabilité climatique est, elle, peu présente dans l'analyse. Deux années climatiques ont été prises en compte dans les **Chapitres 2 et 3** mais en raison du caractère pérenne de la culture, l'effet du climat est partiellement confondu avec l'âge de la culture. Ce sont alors les modèles qui permettraient de le prendre en compte plus largement.

Une autre limite de la démarche de couplage modèle-mesure utilisée dans ce travail est qu'elle est lourde à mettre en place et difficilement généralisable à l'introduction de toute nouvelle culture dans un territoire. D'autres dispositifs sont envisageables pour collecter des données de rendement. Il serait possible de recourir à l'expertise en acceptant qu'elle ne repose que sur une ou deux personnes alors qu'elle repose sur minimum cinq-six experts dans le paramétrage classique de PerSyst. Par ailleurs, les données pourraient être recueillies par enquête auprès des agriculteurs ou des organismes de collecte puis reliées à des bases de données sol. Toutefois, dans cette configuration, les données recueillies ainsi que le diagnostic qui en découle auraient été moins précis. Si des données expérimentales avaient été disponibles sur certains sols de la région d'étude, il aurait pu être également intéressant de les utiliser, sous réserve de pouvoir appréhender l'écart entre rendement expérimental et rendement commercial.

3.2. Intérêts et limites du dispositif de conception / evaluation de systèmes de culture

Le dispositif de conception mis en place repose sur un atelier de co-conception caractérisé (i) par des objectifs précis établis au préalable et (ii) par la mise en commun de connaissances locales et de connaissances expertes (Monnot, 2011).

La mise en place des objectifs est généralement considérée comme une des premières étapes du processus de conception car il est important qu'ils soient partagés par l'ensemble des membres de l'atelier (Lançon *et al.* 2008). Cette étape est précédée d'une caractérisation des enjeux du territoire concerné. Dans ce travail, l'origine du processus de conception vient de la recherche, soit de l'extérieur de la région d'étude, ce qui justifie d'avoir procédé différemment. Toutefois, l'existence de textes réglementaires et en particulier de la directive EnR a permis de fixer des objectifs facilement partageables par les membres de l'atelier. Cela dit, les contraintes fixées par la directive EnR ont fait l'objet d'une « traduction » : l'objectif de réduction des émissions de gaz à effet de serre a ainsi été transposé de l'ensemble de la filière au système de culture. La nécessité de réduire les impacts environnementaux locaux a été reformulée en fonction du contexte français (plan Ecophyto 2018, loi Grenelle sur les aires d'alimentation de captage). Or, le déroulement de l'atelier montre que les systèmes de culture proposés sont extrêmement dépendants des objectifs fixés, comme le montre le système de culture avec M. giganteus proposé en sol argilo-calcaire moyen (CC) (**cf. Chapitre 6 – 2.1**).

Exprimer ces objectifs différemment aurait donc eu de l'influence sur les résultats obtenus. Une démarche de conception / évaluation comporte en théorie plusieurs itérations: à l'issue d'une première étape de conception, les systèmes de culture proposés sont évalués, ce qui fournit la matière à un nouveau travail de conception et ainsi de suite. Le travail réalisé ici ne repose que sur un seul atelier de co-conception, ce qui est bien sûr insuffisant. Toutefois, les experts locaux présents avaient déjà travaillé ensemble lors du paramétrage de PerSyst : à cette occasion, les principaux sols de la région ou encore différentes catégories d'itinéraires techniques avaient été décrits collectivement et ont servi d'outils lors de l'atelier. La co-conception s'est donc appuyée sur une dynamique collective déjà existante. En raison de l'origine externe de la demande, le risque d'essoufflement de cette dynamique si plusieurs boucles de conception / évaluation avaient été mises en place n'aurait pas été négligeable.

Les connaissances expertes ont été mobilisées de deux manières. Tout d'abord, le travail de co-conception en lui-même a été précédé de présentations générales par les experts scientifiques concernant les enjeux liés à la production de bioénergie, les principales cultures candidates et les sources d'émissions de gaz à effet de serre liées à la production agricole. La co-conception a ensuite bénéficié d'interactions entre les experts scientifiques et les experts locaux. Les objectifs fixés en termes de réduction des émissions de GES (de 50%) ont été atteints par les systèmes de culture qui ont été conçus (comme l'indique l'évaluation *ex ante* de ces systèmes de culture réalisée dans le **Chapitre 5**), ce qui permet de penser que le dispositif mis en place a été efficace. Toutefois, l'analyse des systèmes de culture proposés (cf. **Chapitre 5 – 3.1** et **Chapitre 6 – 2.2**) montre que le raisonnement de ces systèmes de culture en termes d'effets précédents et cumulatifs reste limité puisqu'elle ne repose que sur les légumineuses ; la construction des systèmes de culture repose sinon sur l'insertion de cultures moins exigeantes en intrants. Il est possible que ces effets ne soient pas suffisamment connus par les experts locaux. A la suite de Zegada-Lizarazu et Monti (2011), cela suggère qu'il serait nécessaire de mieux caractériser ces effets et d'améliorer leur prise en compte dans la construction d'un système de culture. Par ailleurs, ajouter des experts scientifiques « effets précédents et cumulatifs » dans le dispositif de conception pourrait améliorer la prise en compte de ces effets dans le raisonnement des systèmes de culture.

En raison des objectifs fixés, les systèmes de culture contenant des cultures énergétiques ont été conçus de deux manières différentes. Construire un système de culture contenant *M. giganteus* faisait partie des objectifs : par conséquent, la construction est allée dans ce cas de la culture au système de culture. Un panel de cultures candidates avait par ailleurs été proposé. Pour concevoir des systèmes de culture comprenant ces dernières, les membres de l'atelier sont cette fois partis des objectifs visés à l'échelle du système de culture pour choisir les cultures. Si les objectifs à l'échelle du système de culture ont été atteints dans les deux cas, la construction « système de culture vers culture » est moins pertinente pour étudier les mérites d'une ressource candidate en particulier. Pour éclairer la réflexion sur les mérites des différentes cultures candidates, il serait également nécessaire de partir de la culture, ou plutôt de la catégorie de cultures et d'aller vers un système de culture conçu pour valoriser au mieux la culture étudiée. On pourrait ainsi concevoir un système de culture basé uniquement sur des résidus ou encore un système de culture basé uniquement sur des cultures dédiées annuelles.

Concevoir des systèmes de culture comprenant *M. giganteus* implique de raisonner sur un temps long. Ces systèmes de culture se caractérisent également par une plus grande variabilité des valeurs annuelles des indicateurs ; c'est notamment le cas des indicateurs relatifs à la qualité de l'eau. Les autres systèmes de culture sont eux aussi concernés par cette variabilité, bien que dans une moindre mesure. Il serait nécessaire d'améliorer la prise en compte de cette variabilité dans l'évaluation des systèmes de culture. La durée des systèmes de culture comprenant *M. giganteus* invite également à comparer la résistance des différents systèmes de culture proposés à des changements de contexte, en particulier de contexte économique. L'utilisation de méthodes de prospective pourrait permettre de construire différents « futurs possibles » et de comparer les systèmes de culture pour chacun de ces futurs.

Notons enfin que les membres de l'atelier ont fait des propositions qui n'ont pas pu être évaluées : c'est le cas du sorgho cultivé en dérobé entre du triticale et du maïs ou encore de la luzerne implantée sous couvert de maïs. Les outils actuels ne sont pas paramétrés pour évaluer de telles propositions, autant pour la partie rendement que pour la partie azote. Une évolution des outils est donc nécessaire car de telles propositions méritent d'être discutées à l'échelle du système de culture en raison des effets précédents et cumulatifs potentiels associés, notamment en ce qui concerne les ressources du sol. Compte-tenu du poids de la fertilisation dans le calcul des bilans de gaz à effet de serre, il serait également important de concevoir et d'évaluer des stratégies de fertilisation à base de produits organiques. De telles stratégies n'étaient pas encore évaluables avec PerSyst au moment de son utilisation.

4. Perspective: de la parcelle au territoire

La démarche mise en place dans ce mémoire de thèse se situe à l'échelle de la parcelle agricole. Nous avons déjà mis en évidence qu'une évaluation à l'échelle de la filière est nécessaire à la fois pour les émissions de gaz à effet de serre, mais aussi pour les bilans gaz à effet de serre. Ces derniers permettent en effet d'estimer les émissions de gaz à effet de serre évitées par la production de biocarburants afin de comparer les différentes ressources candidates entre elles et avec les combustibles fossiles. Il serait également nécessaire de passer à l'échelle du territoire pour pouvoir raisonner en termes de bassin d'approvisionnement. Ce changement d'échelle serait d'autant plus nécessaire en raison des enjeux qui pèsent sur la production de bioénergie à partir de ressources agricoles. En effet, des enjeux tels que les impacts environnementaux locaux, qu'il s'agisse des impacts sur la ressource en eau (en qualité et en quantité) ou encore sur la biodiversité, impliquent une prise en charge à l'échelle du territoire. Quand à la concurrence avec la production alimentaire, elle ne peut être efficacement appréhendée qu'à une échelle spatiale encore plus large. Par ailleurs, des synergies entre agriculture et élevage ou encore entre production agricole et usines de transformation sont envisageables à l'échelle du territoire (FAO, 2011). Il s'agit de valoriser les déchets et co-produits de chaque activité par des approches cycliques : utiliser la valeur fertilisante ou énergétique des déjections animales, valoriser les co-produits issus de la transformation de la biomasse pour l'alimentation du bétail ou la fertilisation des cultures… Toutefois, notre travail montre que le passage à l'échelle du territoire n'est pas immédiat. En particulier, il ne peut pas reposer uniquement sur une caractérisation des types de sol puisque la variabilité des rendements ne dépend pas uniquement de ces derniers mais aussi du type de parcelles, c'est-à-dire de son histoire (précédent cultural), de sa forme, de sa surface ou encore de son environnement (distance au siège d'exploitation, accessibilité, appartenance à une zone à enjeux environnementaux). Le diagnostic agronomique mené dans le **Chapitre 2** apporte les éléments nécessaires pour prendre en compte à la fois le type de sol et le type de parcelle mais une réflexion méthodologique serait nécessaire afin d'utiliser ces éléments pour construire des scénarios d'approvisionnement à l'échelle d'un territoire.

Le passage à l'échelle du territoire est d'autant plus important que les usines de production de bioéthanol de seconde génération seront des structures de taille importante de façon à pouvoir réduire les coûts de production. Ces structures vont donc requérir de larges volumes de biomasse. Face à cette perspective, nous avons déjà mentionné que Zegada-Lizarazu et Monti (2011) s'interrogent sur l'opportunité de mettre en place des systèmes de culture composés uniquement de cultures à débouchés énergétiques. De tels systèmes de culture leur paraissent avoir un intérêt limité en raison de la faible gamme de cultures présentant un haut potentiel de production. A notre avis, l'intérêt limité de ces systèmes de culture vient plutôt du risque de se priver de cultures ayant des effets rotationnels intéressants. Il paraît donc plus intéressant de concevoir des systèmes de culture mixtes, comprenant des cultures à vocation énergétique et à vocation alimentaire. A partir de ce constat, l'étape suivante est de se demander s'il faut privilégier une seule ressource, par exemple *M. giganteus*, ou combiner sur le territoire la production de plusieurs ressources énergétiques, tout en restant dans un nombre raisonnable afin de tenir compte de possibles contraintes liées à la phase de transformation. Nous avons montré l'intérêt de planter *M. giganteus* dans des zones à enjeux environnementaux du fait des faibles risques de pertes en nitrates constatés pour cette culture (**Chapitre 3**). Nous avons également rappelé qu'il est fréquemment envisagé de planter cette culture dans des terres marginales, même si nous avons souligné que cette stratégie dépend de la définition donnée aux terres marginales et qu'elle comporte certains risques (**Chapitre 2 et Chapitre 6 – 1.2**). Il est toutefois peu probable que l'ensemble de ces surfaces suffise à approvisionner une usine de biocarburants de deuxième génération. Rowe *et al.* (2009) mettent de plus en garde contre un déploiement trop large de *M. giganteus* à l'échelle d'un territoire en raison des impacts paysagers et du risque de diminution de la recharge des nappes phréatiques. Il semblerait par conséquent plus durable d'approvisionner une usine avec plusieurs ressources. Si ces ressources sont récoltées à des dates différentes, ce qui est le cas si l'on combine par exemple *M. giganteus*, tiges de luzerne et résidus de culture, cela permettrait par ailleurs d'étaler le calendrier d'approvisionnement de l'usine. A l'échelle de l'exploitation agricole, cet étalement est également intéressant car il permet d'améliorer la répartition des pointes de travail et des flux monétaires. Que ce soit l'exploitation agricole, une entreprise de travaux agricoles ou l'usine qui possède le matériel de récolte, cet étalement améliore aussi la rentabilité du matériel. Enfin, pouvoir choisir entre différentes ressources permet à l'agriculteur d'optimiser l'utilisation de sa surface : selon qu'il possède de nombreux hectares situés dans une zone à enjeux environnementaux, de nombreuses parcelles contraignantes, ou à l'inverse un parcellaire simple et groupé, l'intérêt de *M. giganteus* comparé à d'autres ressources énergétiques ne sera pas le même. En revanche, la possibilité d'intégrer une ou des nouvelles cultures est à raisonner en fonction des contraintes de l'exploitation. Zegada-Lizarazu et Monti (2011) rappellent ainsi que l'adoption de systèmes de culture diversifiés présente certaines contraintes pour l'agriculteur : ces contraintes peuvent être organisationnelles ou encore liées à un manque de familiarité avec de nouvelles cultures. Bocquého (2012) a également montré que l'adoption d'une culture pérenne comme *M. giganteus* par un agriculteur dépend de son aversion au risque. Il semble donc que raisonner l'approvisionnement d'une usine reposant sur plusieurs ressources nécessite de s'appuyer non seulement sur l'échelle du territoire, mais aussi sur celle de l'exploitation agricole. Pour terminer, il convient de préciser que la problématique de l'approvisionnement se pose tout à fait différemment pour d'autres types de débouchés énergétiques comme la méthanisation ou la combustion qui font en France l'objet d'un dimensionnement beaucoup plus réduit.

Conclusion générale

Miscanthus x *giganteus* est une culture candidate à la production de biocarburants de deuxième génération qui suscite un vif intérêt. C'est en effet une plante pérenne en C4 dont on attend de hauts rendements associés à de faibles impacts environnementaux. Ce travail de thèse avait pour objectif de contribuer à l'évaluation de la durabilité de la culture de *M. giganteus* (i) en caractérisant la variabilité des rendements et des pertes de nitrates en parcelles agricoles et en identifiant les facteurs responsables de cette variabilité, (ii) en modélisant l'évolution des rendements sur l'ensemble du cycle de vie de la culture et (iii) en mettant en œuvre une évaluation *ex ante* de systèmes de culture incluant cette culture, par comparaison avec des systèmes de cultures incluant d'autres ressources agricoles candidates à la production de biocarburants de deuxième génération. L'hypothèse sous-jacente à ce travail est que le système de culture est une échelle pertinente pour comparer une grande diversité de ressources agricoles candidates : en effet, toute ressource agricole est théoriquement candidate puisque les biocarburants de deuxième génération sont produits à partir de la lignocellulose, constituant majeur des parois végétales. Cette diversité s'exprime non seulement en termes d'espèces (céréales, cultures oléagineuses, légumineuses, cultures fourragères, cultures ligneuses) mais aussi de durée de vie (culture annuelle, pluriannuelle ou pérenne) et d'organes de la plante utilisée (plante entière ou tiges/pailles).

L'étude de *M. giganteus* en parcelles agricoles repose sur une démarche de diagnostic agro-environnemental menée dans un réseau de parcelles de *M. giganteus* plantées en 2009 et 2010 et localisées en Bourgogne. Ce diagnostic montre que les résultats obtenus en termes de rendements (11,2 t MS ha^{-1} pour la deuxième année de croissance ; 15,3 t MS ha^{-1} pour la troisième) et de pertes de nitrates hivernales (6 kg N ha^{-1} ; 12 mg NO_3^{-1} 1^{-1}) sont en moyenne comparables avec ceux obtenus en conditions expérimentales. Ils sont par contre caractérisés par une variabilité supérieure. Comme en conditions expérimentales, cette variabilité est en partie expliquée par l'âge de la culture : les rendements augmentent avec l'âge tandis que les pertes de nitrates diminuent. Toutefois, cette variabilité est également due à la présence dans le dispositif de sols moins favorables que ceux sur lesquels sont généralement menées les expérimentations. Quand il s'agit des pertes de nitrates pendant l'hiver, nous avons montré que les sols peu profonds, caillouteux et/ou sableux présentent un risque de lessivage élevé alors que les sols profonds à tendance hydromorphe sont caractérisés par un lessivage extrêmement faible. Nous avons également montré que la variabilité des rendements s'explique principalement par la variabilité du nombre de tiges par m^2 lors de l'année d'implantation de *M. giganteus*. Des parcelles humides occupées avant la plantation de *M. giganteus* par des jachères longue durée présentent un risque d'échec de la plantation plus élevé (se traduisant par un faible nombre de tiges par m^2). En plus du type de sol et de l'histoire culturale, le type de parcelles considéré seul est également un facteur de variabilité des rendements observés : le risque d'échec de la plantation est ainsi plus élevé sur les parcelles éloignées du siège de l'exploitation, tandis que le risque de pertes à la récolte est plus élevé sur de petites parcelles et/ou des parcelles à la forme très irrégulière.

L'évolution des rendements de *M. giganteus* sur l'ensemble du cycle de vie de la culture a été étudiée à l'aide d'une comparaison de modèles d'évolution des rendements menées sur 42 séries d'évolution à long terme des rendements recueillies dans différents pays européens (Grande-Bretagne, Danemark, Autriche, Irlande, Allemagne). Le modèle qui s'ajuste le mieux est un modèle exponentiel. Il comporte une hypothèse de déclin suggérant que le cycle de culture de *M. giganteus* se décrit en trois phases : (i) une phase d'établissement où les rendements augmentent (qui dure en moyenne 8,3 ans) (ii) une phase où la culture est en pleine production (rendement moyen maximum = 16,8 t/ha), et (iii) une phase où les rendements diminuent. Les caractéristiques de ces trois phases (valeurs de rendements, durée) varient fortement entre sites. Le rendement maximum est dépendant de la latitude de l'essai ($r^2 = 0.67$) : les valeurs maximales de rendement obtenues pendant la phase de pleine production augmentent ainsi du Nord au Sud. La durée de la phase d'établissement de la culture dépend du type de plantation : celle-ci est plus élevée quand la parcelle est plantée avec des rhizomes (par rapport à des plantations avec des micro-plants). L'intensité de déclin des rendements est extrêmement variable entre sites et cette variabilité reste à l'heure actuelle inexpliquée.

Un dispositif de conception et évaluation de systèmes de culture a enfin été mis en place afin de comparer des systèmes de culture comprenant *M. giganteus* avec des systèmes de culture comprenant d'autres ressources candidates à la production de biocarburants de deuxième génération. La phase de conception s'est appuyée sur un atelier de conception à dires d'experts réalisé en Bourgogne. La phase d'évaluation a été réalisée à l'aide de modèles, dont le modèle PerSyst, paramétré en Bourgogne, qui permet d'estimer le rendement d'une culture en fonction du pédo-climat et du système de culture (succession de cultures et itinéraire technique). Les connaissances acquises sur *M. giganteus* concernant (i) le rendement et les pertes de nitrates en parcelles agricoles et (ii) l'évolution à long terme des rendements ont été utilisées pour l'évaluation grâce à plusieurs couplages modèle-mesures. La comparaison des deux catégories de systèmes de culture conçue lors de l'atelier montre que les résultats de l'évaluation multicritère sont sensibles (i) au rendement de *M. giganteus* et (ii) au poids de *M. giganteus* dans le système de culture. D'un point de vue environnemental (pertes de nitrates, utilisation de phytosanitaires, émissions de gaz à effet de serre) et énergétique, les systèmes de culture incluant *M. giganteus* sont globalement meilleurs que ceux incluant d'autres ressources énergétiques. Les résultats économiques sont par contre très sensibles au niveau de rendement de *M. giganteus*. Les deux catégories de systèmes de culture à vocation énergétique sont meilleures au plan environnemental que le système de référence conventionnel à base de colza-blé-orge auquel ils étaient comparés. Ils sont également meilleurs qu'un système de culture intégré grâce à l'insertion de cultures pluri-annuelles (luzerne) ou pérennes (*M. giganteus*). Les résultats économiques sont à nouveau plus variables en fonction du type de sol et des niveaux de rendements des différentes cultures.

Parmi les autres ressources candidates étudiées, la luzerne, dont les tiges peuvent être utilisées pour produire du bioéthanol de deuxième génération, présente plusieurs atouts. Elle se caractérise par de faibles impacts environnementaux alors qu'elle maintient un bon niveau de production sur des sols où la disponibilité en eau est plus réduite. L'insertion de la luzerne a également un impact positif sur les résultats d'évaluation multicritère d'autres ressources comme les pailles de céréales qui bénéficient des effets précédents et cumulatifs associés à cette culture. L'intérêt des pailles de céréales ou des plantes entières comme l'ensilage de maïs ou de triticale dépend de leur niveau de rendements par type de sol comparé à ceux de *M. giganteus* et de la luzerne.

Les résultats de ce travail concernant *M. giganteus* permettent de préciser les niveaux de rendements que l'on peut attendre de la culture en conditions agricoles, ainsi que les risques d'impacts environnementaux locaux en termes de qualité de l'eau pour les trois premières années de culture. Ils permettent également d'enrichir la réflexion concernant la production de *M. giganteus* en terres marginales. Enfin, l'ensemble des résultats de ce travail, obtenus à l'échelle de la parcelle, pourraient être valorisé à l'échelle du territoire dans le but de construire des scénarios d'approvisionnement tenant compte de la diversité des milieux et des conditions agricoles existant à cette échelle.

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Annexes

Annexe 1: Description of the experimental units (EU) (Chapitre 4)

Reference	Location	EU	Duration[1]	Nb	P.M[2]	Density (pl/m2)	Fertilization	Yield measurement characteristics				Soil	Geographical coordinates (DD)	Climate[3]
								Surface (m^2)	Type[4]	Repetition	Harvest dates[5]			
Jorgensen, 1996	DK – Hornum**[1]**	**1**	16 (1983-1998)	13	MP	0.5	70 to 100 kg N	4 to 16	S	NO	Early Spring	Sandy loam	56.8N-9.4E	7.7 // 493
Jorgensen, 1996	DK – Hornum**[1]**	**2**	16 (1983-1998)	13	MP	1	70 to 100 kg N	4 to 16	S	NO	Early Spring	Sandy loam	56.8N-9.4E	7.7 // 493
Jorgensen, 1996	DK – Hornum**[1]**	**3**	17 (1983-1999)	14	MP	2	70 to 100 kg N	4 to 16	S	NO	Early Spring	Sandy loam	56.8N-9.4E	7.7 // 493
Jorgensen, 1996	DK – Hornum**[1]**	**4**	16 (1983-1998)	13	MP	4	70 to 100 kg N	4 to 16	S	NO	Early Spring	Sandy loam	56.8N-9.4E	7.7 // 493
Laerke, pers. comm.	DK – Foulum**[2]**	**5**	15 (1994-2008)	7	R	0.8	0 kg N			NO	Mid-March to early May	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**6**	15 (1994-2008)	7	R	0.8	75 kg N[6]			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**7**	15 (1994-2008)	7	R	0.8	150 kg N5			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**8**	15 (1994-2008)	7	R	1.7	75 kg N5			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**9**	15 (1994-2008)	8	R	0.8	150 kg N5			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**10**	15 (1994-2008)	7	R	1.7	75 kg N5			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Laerke, pers. comm.	DK – Foulum**[2]**	**11**	15 (1994-2008)	9	R	0.8	0 kg N			NO	Idem EU 5	Sandy loam	56.5N-9.6E	8.1 // 658
Christian *et al.* 2008	UK – Harpenden **[3]**	**12**	18 (1993-2010)	18	MP	4	0 kg N; K every year until GY9, except GY7 (116 to 290 kg); P in GY1 and 8 (100 and 58 kg)	36	S	YES (3)	Early Feb. until 2006; then early Spring	Silty clay loam	51.8N-0.4E	10.2 // 750
Christian *et al.* 2008	UK – Harpenden **[3]**	**13**	18 (1993-2010)	18	MP	4	60 kg N; P and K: idem EU 12	36	S	YES (3)	Idem EU 12	Silty clay loam	51.8N-0.4E	10.2 // 750
Christian *et al.* 2008	UK – Harpenden **[3]**	**14**	18 (1993-2010)	18	MP	4	120 kg; P and K: idem EU 12	36	S	YES (3)	Idem EU 12	Silty clay loam	51.8N-0.4E	10.2 // 750

[1] The second year mentioned is the last year for which yield data were available, but does not correspond to the last year of the experiment.
[2] P.M : planting mode ; MP = micro-propagation; R = rhizomes
[3] Mean annual temperature (°C) and mean annual rainfall (mm)
[4] S = surface; P = plant; M = machine
[5] In that column is displayed the between-year harvest date variability.
[6] Fertilization was different during the first three years.

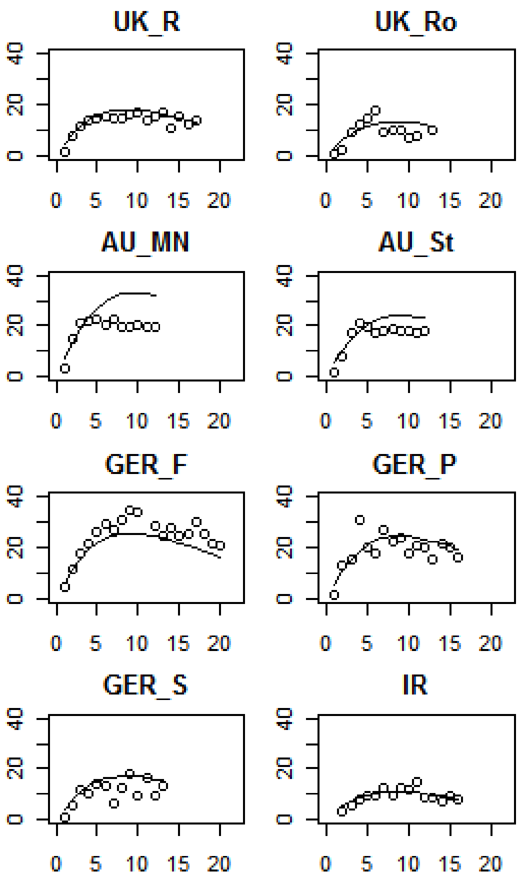
Reference	Location	EU	Duration[7]	Nb	P.M[8]	Density (pl/m2)	Fertilization	Yield measurement characteristics: Surface (m^2)	Type[10]	Repetition	Harvest dates[11]	Soil	Geographical coordinates (DD)	Climate[9]
Riche *et al.* 2008	UK – Harpenden**[4]**	**15**	14 (1997-2010)	13	MP	2	60 kg N and 95 to 130 kg K every year until GY6; P until GY3 (44 kg)	25	S (M)	YES (3)	Early Feb. until 2006; early Spring	Silty clay loam	51.8N-0.4E	10.2 // 750
Riche *et al.* 2008	UK – Harpenden**[4]**	**16**	14 (1997-2010)	13	MP	2	Idem EU 15	25	S (M)	YES (3)	Idem EU 15	Silty clay loam	51.8N-0.4E	10.2 // 750
Riche *et al.* 2008	UK – Harpenden **[4]**	**17**	14 (1997-2010)	13	MP	2	Idem EU 15	25	S (M)	YES (3)	Idem EU 15	Silty clay loam	51.8N-0.4E	10.2 // 750
Riche *et al.* 2008	UK – Harpenden **[4]**	**18**	14 (1997-2010)	13	MP	2	Idem EU 15	25	S (M)	YES (3)	Idem EU 15	Silty clay loam	51.8N-0.4E	10.2 // 750
Liebhard, 2002	AUS – Ilz **[5]**	**19**	13 (1989-2001)	13	MP	1	Every year from GY 2 50 kg N, 36 kg P and 150 kg K (22.5 kg MgO)	10	P	YES (3)	End of February	Brown earth.	48.2N-14.4E	9.0 // 820
Liebhard, 2002	AUS – Mackgraf-Neusiedl**[6]**	**20**	12 (1989-2000)	12	MP	1	Idem EU 19	10	P	YES (3)	Idem EU 19	Brown earth	48.3N-15.9E	9.6 // 558
Liebhard, 2002	AUS – Michelndorf **[7]**	**21**	12 (1989-2000)	12	MP	1	Idem EU 19	10	P	YES (3)	Idem EU 19	Chernozem	48.3N-16.6E	9.4 // 620
Liebhard, 2002	AUS – St Florian **[8]**	**22**	13 (1989-2001)	13	MP	1	Idem EU 19	10	P	YES (3)	Idem EU 19	Brown earth	47.8N-16.4E	9.0 // 853
Liebhard, 2002	AUS – Steinnbrunn **[9]**	**23**	12 (1989-2000)	12	MP	1	Idem EU 19	10	P	YES (3)	Idem EU 19	Para-brown earth	47.8N-15.9E	9.0 // 820
Fritz and Formowitz, pers. comm.	GER – Günterleben **[10]**	**24**	22 (1989-2010)	20	R	1.1	0 kg N; P and K every year	90	S (M)	YES (2)	Early April	Brown earth	49.9N-9.9E	10.4 // 606
Fritz and Formowitz, pers. comm.	GER – Günterleben **[10]**	**25**	22 (1989-2010)	20	R	1.1	50 kg N; P and K every year	90	S (M)	YES (2)	Idem EU 24	Brown earth	49.9N-9.9E	10.4 // 606
Fritz and Formowitz, pers. comm.	GER – Günterleben **[10]**	**26**	22 (1989-2010)	20	R	1.1	100 kg N; P and K every year	90	S (M)	YES (2)	Idem EU 24	Brown earth	49.9N-9.9E	10.4 // 606
Fritz and Formowitz, pers. comm.	GER – Günterleben **[10]**	**27**	22 (1989-2010)	20	R	1.1	150 kg N; P and K every year	90	S (M)	YES (2)	Idem EU 24	Brown earth	49.9N-9.9E	10.4 // 606
Fritz and Formowitz, pers. comm.	GER – Günterleben **[10]**	**28**	22 (1989-2010)	20	R	1.1	250 kg N; P and K every year	90	S (M)	YES (2)	Idem EU 24	Brown earth	49.9N-9.9E	10.4 // 606[12]

[7] The second year mentioned is the last year for which yield data were available, but does not correspond to the last year of the experiment.
[8] P.M : planting mode ; MP = micro-propagation; R = rhizomes
[9] Mean annual temperature (°C) and mean annual rainfall (mm)
[10] S = surface; P = plant; M = machine
[11] In that column is displayed the between-year harvest date variability.

Reference	Location	EU	Duration[32]	Nb	P.M[33]	Density (pl/m2)	Fertilization	Yield measurement characteristics				Soil	Geographical coordinates (DD)	Climate[34]
								Surface (m^2)	Type[35]	Repetition	Harvest dates[36]			
Fritz and Formowitz, pers. comm.	GER – Freising**[11]**	**29**	20 (1991-2010)	19	R	1.2	0 kg N; P and K every year	50	S (M)	YES (3)	Mid-March to mid-April	Brown earth	48.4N-1.7E	10.2 // 845
Fritz and Formowitz, pers. comm.	GER – Freising**[11]**	**30**	20 (1991-2010)	19	R	1.2	75 kg N; P and K every year	50	S (M)	YES (3)	Idem EU 29	Brown earth	48.4N-11.7E	10.2 // 845
Fritz and Formowitz, pers. comm.	GER – Freising**[11]**	**31**	20 (1991-2010)	19	R	1.2	150 kg N; P and K every year	50	S (M)	YES (3)	Idem EU 29	Brown earth	48.4N-11.7E	10.2 // 845
Fritz and Formowitz, pers. comm.	GER – Puch **[12]**	**32**	20 (1991-2010)	19	R	1.2	75 kg N; P and K every year	50	S (M)	YES (3)	Mid-March to early May	Para-brown earth	48.2N-11.2E	10.4 // 866
Grunert, pers. comm.	GER – Kalkreuth **[13]**	**33**	16 (1995-2010)	16	MP	1.5	None	6.5	S	YES (6)	End Jan. to mid-april	Strong sandy loam	51.3-13.6E	8.5 // 595
Grunert, pers. comm.	GER – Zwenkau**[14]**	**34**	16 (1995-2010)	13	MP	1.3	60 kg N until GY 11; P and K every 2 years	6.5	S	YES (6)	Mid -Jan. to mid-april	Sandy loam	56.2N-12.3E	8.6 // 545
Grunert, pers. comm.	GER – Spröda**[15]**	35	13 (1998-2010)	13	MP	1	60 kg N; 30 kg P and 100 kg K every 3 years	15	S	YES (4)	End Jan. to early april	Loamy Sand	51.5N-13.6E	8.8 // 540
Grunert, pers. comm.	GER – Spröda**[15]**	36	13 (1998-2010)	13	MP	1	60 kg N; 30 kg P and 100 kg K every 3 years	15	S	YES (4)	End Jan. to early april	Loamy Sand	51.5N-13.6E	8.8 // 540
Clifton-Brown *et al.*, 2007	IRE – Cashel**[16]**	37	16 (1990-2005)	16	MP	2	Every year except 2 (9 and 10); N: 100 to 120 kg P: 36 kg, K: 72 kg	8 to 12	S	YES (2 to 8)	Early Dec. until GY9; Feb to early March	Loam to sandy loam	52.7N-7.8W	9.9 // 1004

[32] The second year mentioned is the last year for which yield data were available, but does not correspond to the last year of the experiment.
[33] P.M : planting mode ; MP = micro-propagation; R = rhizomes
[34] Mean annual temperature (°C) and mean annual rainfall (mm)
[35] S = surface; P = plant; M = machine
[36] In that column is displayed the between-year harvest date variability.

Annexe 2: Prédiction des rendements de *M. giganteus*



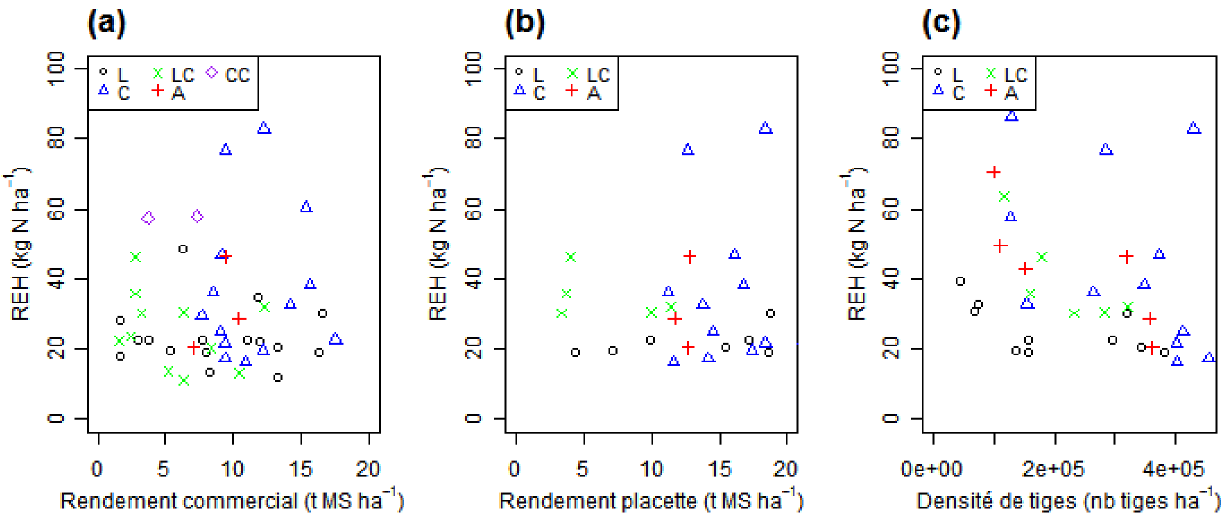
Prédiction des rendements de *M. giganteus* (t MS ha^{-1}) à partir des rendements des années de croissance 2 et 3 pour les sites de la base de données du Chapitre 4.

Les points correspondent aux données, la courbe à la prédiction. Pour les sites avec plusieurs unités expérimentales (EU), une seule est représentée. Les sites danois ne sont pas représentés faute de données pour les années de croissance concernées.

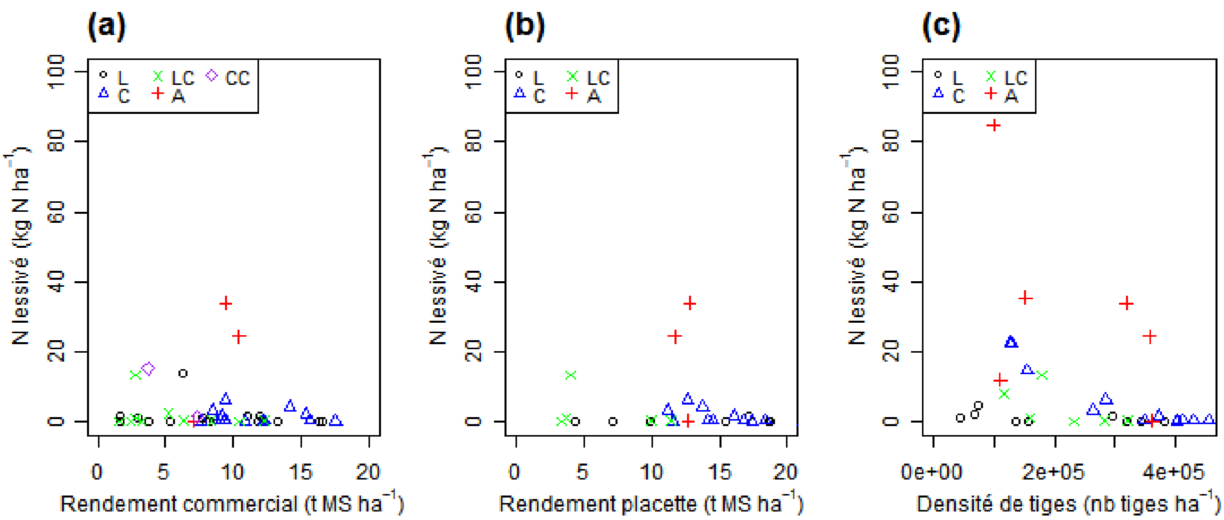
Qualité moyenne de la prédiction du rendement en fonction de l'âge (RMSEP et RMSEP relative), du rendement moyen et du rendement maximum (erreur) estimée sur l'ensemble de sites figurant ci-dessus en fonction du nombre de données de rendement utilisées.

Nombre de données de rendement	2	3	4
RMSEP (t MS ha^{-1})	3,3	3,4	2,5
relRMSEP (%)	22	22	
Erreur (rendement moyen) (t MS ha^{-1})	-0,11	-0,16	-0,14
Erreur (rendement max) (t MS ha^{-1})	0,06	0,02	0,04

Annexe 3: Risque de lixiviation d’azote en fonction du type de sol et du développement de la culture



Reliquat d’azote minéral mesuré en entrée d’hiver par type de sol en fonction a) du rendement commercial, b) du rendement placette, c) de la densité de tiges.



Lixiviation d’azote simulé avec LIXIM par type de sol en fonction a) du rendement commercial, b) du rendement placette, c) de la densité de tiges.

Annexe 4: Description des systèmes de culture conçus pendant l'atelier de conception (Chapitre 5)

Cropping systems' description

Cropping system		**LC1**	**LC2**	**LC3**	**LC4**	**CC1**	**CC2**	**CC3**	**CC4**
Cropping sequence[1, 2]		OSR/WW/WB	OSR/WW/ WB/#S/ WW/#SP	WWs/MISC/ WP/OSR/ WWs/ALF	ALF/WWs/ OSR/#M/#SP/ OSR/WWs	OSR/WW/WB	OSR/WW/ WB/#S/ WW/#SP	MISC + OSR/WW/ WTs/S/SB/WP	ALF/OSR/ WWs/WT
ALF	Tillage[3]	-	-	MB	MB	-	-	-	MB
	N rate[4]	-	-	0	0	-	-	-	0
	P and K rate	-	-	90 – 175	90 – 175	-	-	-	90 – 175
	CP[5]	-	-	-	-	-	-	-	-
OSR	Tillage	RT	RT	RT	RT	RT	RT	RT	MB
	N rate (u N)	170	120*	120	120*	160	110	110	100*
	P and K rate	60 – 60	50 – 50	50 – 50	50 – 50	60 – 60	50 – 50	50 – 50	50 – 50
	CP	2F – 4.5I	0.5F – 2I	0F – 0I	0F – 0I	2F – 4.5I	0.5F – 2I	0.5F – 2I	0.5F – 2I
Maize	Tillage	-	-	-	MB	-	-	-	-
	N rate (u N)	-	-	-	140	-	-	-	-
	P and K rate	-	-	-	40 – 40	-	-	-	-
	CP	-	-	-	2F – 1I	-	-	-	-
SP/WP	Tillage	-	MP	RT	MP	-	MP	MP	-
	N rate (u N)	-	0	0	0	-	0	0	-
	P and K rate	-	40 – 40	40 – 40	40 – 40	-	40 – 40	40 – 40	-
	CP	-	1.5F - 1.5I	1.5F - 1.5I	1.5F - 1.5I	-	1.5F 1.5I	1.5F 1.5I	-

S	Tillage	-	MP	-	-	-	MP	MP	-
	N rate (u N)	-	0	-	-	-	0	0	-
	P and K rate	-	0			-	0	0	-
	CP	-	0F – 1I	-	-	-	0F – 1I	0F – 1I	-
WB/SB	Tillage	MP	MP	-	-	MP	MP	RT	-
	N rate (u N)	140	150	-	-	165	150	90	-
	P and K rate	40 – 40	40 – 40	-	-	40 – 40	40 – 40	40 – 40	-
	CP	2F – 2I – 2R	1.5F – 1I – 1R	-	-	2F – 2I – 2R	1.5F – 1I – 1R	1.5F – 1I – 1R	-
WT	Tillage	-	-	-	-	-	-	RT	RT
	N rate (u N)	-	-	-	-	-	-	110	110
	P and K rate	-	-	-	-	-	-	10 – 50	10 – 50
	CP	-	-	-	-	-	-	1F- 0I	1F- 0I
WW	Tillage	RT	RT	RT	RT	RT	RT	RT	RT
	N rate (u N)	180	150	150	150 (110*)	160	130	130	110*
	P and K rate	0 – 0	0 – 0	10 – 50	10 – 50	0 – 0	0 – 0	0 – 0	10 – 50
	CP	3F – 2I – 2R	2F – 0I – 0R	2F – 0I – 0R	2F – 0I – 0R	3F – 2I – 2R	2F – 0I – 0R	2F – 0I – 0R	2F – 0I – 0R

[1] OSR: oilseed rape; WW: winter wheat; WB: winter barley; SB: spring barley; S: sunflower; SP: spring pea; WP: winter pea; ALF: alfalfa; MISC: *M. giganteus*;s indicates that straw are exported.

[2] # indicated the presence of a cover crop.

[3] MB: mouldboard ploughing; RT: reduced tillage

[4] * indicates that N rate is reduced thanks to the presence of a legume as preceding or ante-preceding crop.

[5] CP = Crop protection: number of fungicides (F), insecticides (I) and regulators (R).·Herbicide applications are not described since they were similar per crop and cropping systems, except for winter wheat (2H in CS1, 0.5H with alfalfa as preceding crop; 1H otherwise) and oilseed rape (1.6H or 1H with alfalfa as preceding crop). NB: Alfalfa does not get any crop protection expect an herbicide treatment during the sowing year (0.3H).

Description of *M. giganteus* management

	MISC A1	MISC A2	MISC A3 and following years	MISC destruction
Tillage	MB	-	-	01/06: crusher (or harvest)
N rate	0	0-	Every 3 years	10/07: crusher + rotavator
			LC-L: CC-L; CC-H: 30	25/07: chisel
			LC-I: 60	25/08: 1H
			LC-H: 80	15/09: chisel
P and K rate	0	0	Every 6 years	
			LC-L: CC-L; CC-H: 15 – 30	
			LC-I: 30 – 60	
			LC-H: 40 – 80	
CP	3H	1H (+1H if necessary)	-	

Annexe 5: PerSyst, a cropping system model based on local expert knowledge

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A large number of alternative cropping systems need to be investigated in order to identify the most suitable ones for a given set of objectives. Few crops models can be used to generate and assess cropping systems because they generally account for a limited number of production factors, and include a large number or parameters that are difficult to estimate. The cropping system model PerSyst was developed to simulate the effect of crop sequence and crop management techniques on yield and nitrogen losses in the environment at a yearly time step. As PerSyst is easy to parameterize from local expert knowledge, it could be implemented in different contexts by the model users themselves.

Model description

In PerSyst, yield is calculated as a function of limiting and reducing factors (Van Ittersum and Rabbinge, 1997). Experts define a potential yield (*i.e.* when only climatic factors reduce yield) for each soil type of the study area. They also assess the yield reduction due to (i) the preceding crop effect, (ii) the frequency of crops affected by the same pests and diseases in the crop sequence, and (iii) soil physical and chemical fertility. This information is integrated in PerSyst at the crop sequence level. The yield reduction is then corrected in function of crop management techniques (sowing period, nitrogen fertilization, number of fungicides, insecticides and other pesticide applications).Nitrogen losses are assessed using the IN indicator of the Indigo environmental assessment method (Bockstaller *et al.* 2008).

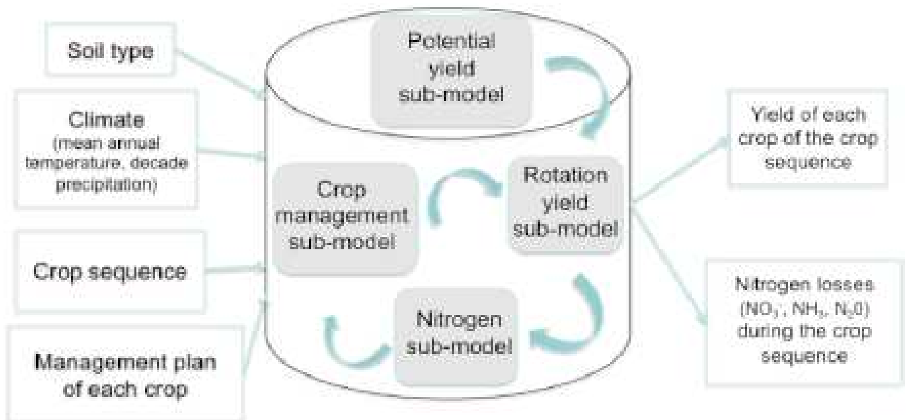

Figure 1: Model description

Methodology for parameter estimation

The main original feature of PerSyst is the integration of local expert knowledge to estimate potential yields and percentages of yield reduction due to limiting factors. Twelve experts (farmers' advisors and agricultural engineers) from Poitou-Charentes (Center-West of France) were asked to assess yield parameters. In the first part of the interview, experts were asked to(i) assess the potential yield of a given crop (ii) specify the main characteristics of the crop management systems and the preceding crop which provides this potential yield, (iii) express their assessments in deciles values to identify the variability in potential yield. Results provided by the individual expert were then discussed collectively and decision rules were designed to synthesize local knowledge (see results section).This methodology combines several characteristics of the Delphi method (Pill, 1971) and of the techniques of elicitation of experts' judgments proposed in the SHELF (Sheffield Elicitation Framework) method (O'Hagan, 2001).

Results and discussion

Table 1 shows an example of results for wheat potential yields in two soil types derived from the expert interviews.

Table 1:Parameter assessment for wheat potential yields in two soil types, a shallow soil (limestone, 40 cm) and a deep soil (loamy soil, 100 cm) (Poitou-Charentes, France). Minimum (maximum) is the min (max) value given among all experts answers. Left table presents the results obtained from the individual step of interviews while results after collective discussion are presented in the right table.

	Shallow soil		Deep soil	
Wheat potential yield	1st decile	9th decile	1st decile	9th decile
Number of answers	7		8	
Mean ($q.ha^{-1}$)	55	71.4	77	95
STD ($q.ha^{-1}$)	12.9	14.4	10.2	8.5
Minimum ($q.ha^{-1}$)	40	55	60	80
Maximum ($q.ha^{-1}$)	80	100	91	105

	Shallow soil		Deep soil	
Wheat potential yield	1st decile	9th decile	1st decile	9th decile
Number of answers	5		6	
Mean ($q.ha^{-1}$)	53	69	77	96
STD ($q.ha^{-1}$)	5.7	5.5	6.9	5.8
Minimum ($q.ha^{-1}$)	45	60	65	90
Maximum ($q.ha^{-1}$)	60	75	85	105

In the second part of the individual step, experts were asked to assess the effect of (i) a shift in the preceding crop, or (ii) a modification of the frequency of crops sensitive to same soil-born pathogens in the crop sequence on yield. They were also asked about the effect of soil-born pest and disease, soil structure, delayed sowing date (and others factors) on yield. The third part of the interview dealt with the consequences of some crop management techniques (and their interactions) on yield. The aim was to identify modifications in the crop management plan that allow compensating partially or totally the reduction of yield and to quantify it. Dexi software (Bohanec, 2008) was used to organize and implement in a generic way, for each crop, the main interactions between techniques (cultivar choice, sowing date and density, fertilization, crop protection, etc.) and their consequence on yield. The collective step led us to adopt the following decision rules: (i) excluding extreme value when more than five responses were given, (ii) averaging of the remaining values. Finally, these rules led us to decrease the range of yield variation within responses for a same soil context, and the final values were accepted by all the experts.

Conclusions

The PerSyst model and the methods used to elicit local experts' knowledge allow local parameter assessment as well as integration of additional knowledge. In the future, we plan to describe potential yield values using probability distributions (instead of point values) and to combine expert knowledge with several sources of experimental data (synthesized by meta-analysis).

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Abstract

Second-generation biofuels could provide renewable energy while reducing the global economy dependence on oil and mitigating climate change. However, their greenhouse gas emission balances, as well as their energy and environmental balances, are discussed, especially when they are produced from agricultural feedstock. The use of agricultural feedstock for energy purposes also raises the issue of competition with food production. In this context, this work contributes to the assessment of the sustainability of *Miscanthus* x *giganteus*, a perennial C4 crop candidate to the production of second-generation ethanol. The objectives of this work are (i) to achieve a multicriteria evaluation of cropping systems based on *M. Giganteus* using data collected in farmers' fields and (ii) to compare these cropping systems with cropping systems including other resources Agricultural candidates for biofuel production. The main contributions of this work are (i) the study of the variability of yields and winter nitrate losses in a network of commercial fields located in Burgundy (France), (ii) the characterization by modeling of *M. giganteus* long-term yield evolution and (iii) the integration of these findings in a process of cropping systems design and assessment aiming at comparing *M. giganteus* with other feedstock candidate to the production of bioethanol. The study of *M. giganteus* in farmers' fields shows that the high variability of yields and nitrate losses is linked to (i) crop age, (ii) soil type and (iii) the type of field (*i.e.* cultural history, size, shape, and environment). Contrasting yield scenarios, built by combining data collected in commercial fields with a long-term yield evolution model, show that the sensitivity of assessment results regarding yields depends on the assessment field. The insertion of *M. giganteus* in a cropping system can significantly improve the greenhouse gas emission balance as well as the environmental balance, compared with a cropping system based on a short cropping sequence. Economic results depend strongly on *M. giganteus* yield. Other agricultural feedstocks are also interesting, especially on soils where the yield potential of *M. giganteus* is low: this is particularly the case of alfalfa stems, which can be used for second-generation ethanol production.

Keywords

Miscanthus x *giganteus*, yield gap analysis, nitrate leaching, modeling, design and assessment of cropping systems, energy oriented cropping system

Résumé

Les biocarburants de deuxième génération, dont les procédés de transformation sont encore en phase expérimentale, pourraient constituer une source d'énergie renouvelable permettant de réduire la dépendance de l'économie mondiale au pétrole tout en luttant contre le changement climatique. Toutefois, leurs bilans gaz à effet de serre, énergétique et environnementaux restent discutés, en particulier lorsqu'ils sont produits à partir de ressources agricoles. L'utilisation de ressources agricoles à des fins énergétiques soulève aussi la question de la concurrence avec la production alimentaire. Dans ce contexte, ce travail contribue à l'évaluation de la durabilité de *Miscanthus* x *giganteus*, culture pérenne en C4 utilisable uniquement à des fins non-alimentaires parmi lesquelles figure la production d'éthanol de deuxième génération. Les objectifs de ce travail sont (i) de réaliser une évaluation multicritère de systèmes de culture comprenant la culture de *M. giganteus* à partir de données recueillies en parcelles agricoles et (ii) de comparer ces systèmes de culture à des systèmes de culture comprenant d'autres ressources agricoles candidates à la production de biocarburants. Les principaux apports de ce travail viennent de (i) de l'étude de la variabilité des rendements et des pertes hivernales de nitrates dans un réseau de parcelles agricoles localisées en Bourgogne, (ii) de la caractérisation par modélisation de l'évolution des rendements de la culture à long-terme et (iii) de l'intégration de ces connaissances dans une démarche de conception et évaluation de systèmes de culture permettant de comparer *M. giganteus* avec d'autres ressources candidates à la production de bioéthanol. L'étude de *M. giganteus* en parcelles agricoles met en évidence que la forte variabilité des rendements et des pertes de nitrate est liée (i) à l'âge de la culture, (ii) au type de sol et (iii) au type de parcelle (*i.e.* histoire culturale, taille, forme, environnement). Des scénarios contrastés de rendement, construits en combinant les données de rendements commerciaux recueillies en parcelles agricoles avec un modèle d'évolution à long-terme des rendements, montrent que les résultats d'évaluation sont plus ou moins sensibles au rendement de *M. giganteus*. L'insertion de *M. giganteus* dans un système de culture permet d'améliorer nettement les bilans gaz à effet de serre et environnementaux du système de culture comparé à un système de culture à rotation courte, tandis que les résultats économiques sont très sensibles au rendement obtenu. D'autres ressources agricoles paraissent également prometteuses, en particulier sur des sols où le potentiel de rendement de *M. giganteus* est moins élevé : c'est en particulier le cas de la luzerne dont les tiges peuvent servir à la production d'éthanol de deuxième génération.

Mots-clés

Miscanthus x *giganteus*, cultures ligno-cellulosiques, diagnostic agronomique, lixiviation de nitrates, modélisation, conception et évaluation de système de culture, système de culture à vocation énergétique