Modeling multi-functional forest management through a social-ecological system framework-based analysis

Mojtaba Houballah

N° d'ordre : D.U. : 0000
EDSPIC : 0000

UNIVERSITÉ Clermont Auvergne

U.F.R Sciences et Technologies

ECOLE DOCTORALE DES SCIENCES POUR L'INGÉNIEUR

THÈSE

Présentée pour obtenir le grade de

DOCTEUR D'UNIVERSITÉ

Spécialité: Informatique/Mathématique

Par **Mojtaba HOUBALLAH**

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Soutenue publiquement le 13 Décembre 2019 devant le jury.

Rapporteurs :	**François BOUSQUET** Directeur de recherche, CIRAD, Montpellier **Samuel BATES** Professeur des universités, ESTHUA, Angers
Examinateur :	**Mabel TIDBALL** Directrice de recherche, INRA, Montpellier
Directeur de thèse :	**Jean-Denis MATHIAS** Directeur de recherche, IRSTEA, Clermont-Ferrand
Co-directeur de thèse :	**Thomas CORDONNIER** Ingénieur - chercheur, IRSTEA, Grenoble

Avant-propos

Cette thèse a été effectuée au centre d'Aubière de l'Institut National de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture (IRSTEA) au sein du Laboratoire d'Ingénierie pour les Systèmes Complexes (LISC).

Je remercie grandement IRSTEA, l'Agence Nationale de la Recherche (ANR-16-CE03-0003), ainsi que la région Auvergne qui, par leur soutien financier, ont permis la réalisation de cette thèse.

Le document qui suit présente une thèse rédigée en anglais, sous forme d'articles scientifiques soumis dans des revues internationales.

ABSTRACT

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The usefulness of forests is spread from their exploitation for timber, tourism, and other functions to maintenance of wildlife, ecological balance, and prevention of soil erosion. In achieving these goals, the essential factor is proper forest management. However, with the increasingly perceived idea that forests are characterized by complex interactions related to biological and social aspects, forest management is facing a challenge, which consists in integrating interrelations between ecological and social systems. While sustainable forest management is originally seen as a constant yield of wood supply, modern ideas of sustainability are broader in scope, embracing all goods and services of the forest. Increasingly, forests are being managed as multi-functional ecosystems. In this vein, forests are progressively seen as complex social-ecological systems (SESs), requiring adaptive and multi-functional management. In this Ph.D. thesis, we consider that the question of management application can be tackled by understanding how shared infrastructures mediate the interaction between human and ecological environment. In particular, for sustainable and multi-functional forest management, the relation between the capacity for production as well as multi-functional use is highlighted with the concept of forest's shared infrastructures that are mainly composed of roads (accessibility utilities). However, dilemmas associated with their provision pose some problems when it is applied in a context of different forest functions with conflicting objectives. Therefore, to fully understand and integrate the role of infrastructure and their governance into ecosystem science, we base our research on three parts. We first combine the use of Ostrom's SES framework and Anderies' robustness framework and apply it to a specific case study (Quatre-Montagne forest, Vercors, France) to highlight how forestry institutions affect forest ecosystem, its functions, and its social arrangements. With this, we link the concept of multi-functional forest management to the multi-functionality of infrastructures. We then develop a mathematical model, based on the first partition, which analyzes the evolution of the forest system and its functions when impacted by decisions of infrastructure provision. We highlight the role of governance calling to attention their role in fostering multi-functional forest management. Finally, we apply mathematical tools such as viability theory to identify management techniques and approaches that define a first step in characterizing adaptive managements for safe operating spaces in multi-functional forests.

Keywords: Social-ecological system; robustness framework; forest governance; forest functions; infrastructures;

Acknowledgment

Undertaking this Ph.D. has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from many people.

Foremost, I would like to express my sincere gratitude to my advisors Jean-Denis Mathias and Thomas Cordonnier for the continuous support of my Ph.D. study and research, for their patience, motivation, enthusiasm, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisors and mentors for my Ph.D. study.

Beside my advisors, I would like to thank the rest of my thesis committee: Prof. Francois Bousquet, Prof. Samuel Bates, and Prof. Mabel Tidball, for their insightful comments and hard questions.

I would like to thank the Agence Nationale de la Recherche and Région d'Auvergne for having financially supported this work during the past three years.

I am so happy to have been part of the LISC team in IRSTEA. I would like to thank all the members of the team who have definitely taken a part in the success of this work, thanks to the intellectual and warm atmosphere and serious, but sometimes casual, discussions during coffee breaks. In the past three years, I have experienced the most difficult but also the most beautiful moments, memories that will stay engraved in my mind till the day I die.

It's my fortune to gratefully acknowledge the support of my friends, Mohammed, Ali, and Noura for their support and generous care throughout the research tenure. They were always beside me during the happy and hard moments to push me and motivate me. Special thanks are extended for the support shown from my friends in Lebanon who are countless to mention.

Finally, I acknowledge the people who mean a lot to me, my parents, Ali and Sanaa, for showing faith in me and giving me the liberty to choose what I desired. I salute you all for the selfless love, care, pain, and sacrifice you did to shape my life. I would never be able to pay back the love and affection showered upon by my parents. Also, I express my thanks to my brothers Mohammed and Mostafa, and my sister Malak for their support and valuable prayers.

Contenu

Chapter 1

Introduction

Preface

The objective of this thesis is to couple operational mathematical tools and implementation with the social-ecological system and robustness frameworks in order to define and diagnose variables and dynamics of an exploited forest system highlighting its main forest functions. Two things are expected in work: the first part that deals with an SES framework-based qualitative analysis of a forest case study, which serves as a basis for the second part which considers a mathematical diagnosis using dynamical system tools and viability theory. This introduction recalls the motivation and the rationale, as well as theoretical parts, approached in this thesis, mainly, social ecological-system framework, robustness framework, viability theory, and concepts SOSs and adaptive management.

1.1 Framework of the thesis

1.1.1 Sustainable management of forests

Forests provide a large number of provisioning, regulating, supporting, and cultural functions that stabilize climate, protect plants and animal species, provide food and shelter to local communities, protect critical human infrastructures such as settlements, roads, and railway lines from gravitational natural hazards, and isolate large amounts of carbon as a result of recycling of gases [Nasi et al. 2002, Millennium ecosystem assessments 2005, Bonan 2008, Gamfeldt et al. 2013]. These ecosystem functions are crucial to our survival and humans probably could not live without them [Daily et al. 1997]. These services, as the deal with other nature's services, have also been claimed to be of great economic value [Costanza et al. 1997, Pearce at al. 2001]. Nevertheless, forests face multiple natural and anthropogenic pressures. For instance, changing climate affects tree species composition and assemblage [Ritchie 1986]. Climate-driven forest pressures, which are foreseen to increase along with competing socio-economic demands for forest services will result in multiple drivers of forest environmental change [Seppälä et al. 2009]. The relationship between forests and the environment has been recognized for more than a thousand years, yet forest management practices continue to cause damage to the environment in the form of biodiversity degradation, water quality deterioration, and other adverse effects [Innes 2004]. Given the vital importance of forests for the global climate, it is critical that in the future, all forest uses are conducted in a manner that is more responsible in terms of sustaining the resource [United Nations1992, Kohm & Franklin 1997].

The ideal concept of maintaining a continuous flow of goods and services from the forest has occupied a central place in forestry thinking [Ciancio and Nocentini 1997, Messier et al. 2014]. This way of thinking anticipated a modern view of sustainability, which assumes that there are desirable states for ecosystems, e.g., managed forests that humans can maintain indefinitely. However, there is a rising awareness that "we must face the impossibility of defining a goal of 'sustainability' in a world characterized by extreme complexity, radical uncertainty, and unprecedented change" [Benson and Craig 2014] is pressing towards alterations in the argument on forest management not only from a scientific and technical position but also from a governance perspective. Therefore, the future of forests in sustainable development at all levels is occupying a central objective in forestry science.

Sustainable development starts from the principle that the present level of consumption and its effects on the environment must respect an equilibrium that makes the necessary space for operating for future options [Shah et al. 2008]. A sustainable use of natural resources is thus linked to concrete economic and technical conditions and depends on fundamental human perspectives and social norms at the same time [Basiago 1999]. Sustainability does not express an intention for the use of resources; it rather represents what people and social and political communities recognize as worth saving and managing responsibly [Schmithüsen 2018]. The necessary elements for managing forest resources in a sustainable way depends on the understanding of the ecological and social processes [Hossain et al. 2017] and flexibility in decision making regarding changing societal needs [Mathias et al. 2015].

The term "sustainable forest management" can be traced to the so-called "forest principles". Its guiding objective is to contribute to the management conservation and sustainable development of all types of forests and to provide for their multiple and complementary functions and uses [Forest Principles, UN Rio, 1992]. Although the term "forest principles" emerge from a non-legally binding statement of principles, they bear the marks in a negotiated text with a very general wording and are focused on guidance for the establishment of an enabling framework for sustainable forest management, rather than principles for field-level application of forest management [Wilkie-Loyche et al. 2003]. The concept of sustainable forest management has continued to evolve since 1992 through the international forest policy dialogue and through a large number of country-led and eco-regional initiatives aimed at translating the concept into practice [Davenport et al. 2010].

1.1.2 From sustainability to multi-functionality

Sustainable forest management can be defined as the use of forest resources in a way and at a rate that maintains their biodiversity, productivity, regeneration capacity, and their potential to fulfill now, and in the future the relevant ecological, economic, and social functions [Martin-Garcia and Diez 2012]. It has originally been seen as a constant yield of wood supply but now is broader in scope, embracing all the goods and services of the forest. As a result, progressively, forests are being managed as multi-functional ecosystems [Farrell et al. 2000].

Thus, sustainable forest management expands from its original focus on wood production to include a wide range of different forest uses meeting economic needs, opportunities, and addressing dynamically the changing social and cultural values [Schmithüsen and Seeland 2006]. In a modern business management-oriented definition, as formulated by Speidel [1984], sustainable forestry means the ability of landowners and forest enterprises to produce wood, to care for infrastructural services, and to provide environmental services for the benefit of present and future generations. It means maintaining and creating the entrepreneurial conditions necessary for a permanent and continually optimal fulfillment of economic needs and goals. Therefore, this concept of sustainability combines economic necessities with multiple social and environmental requirements laying foundations towards a broader in scope multi-functional management approach.

Forest multi-functional management, which also highlights the ecological and economic roles of forest ecosystems for society, has become a central objective for several European countries (e.g., France, Italy, and Germany) [Slee 2012]. In this vein, multi-functional forest management practice is defined as a land-use strategy capable of meeting divergent societal interests, supporting forestry practices adaptable to different social groups, and remaining consistent with the principles of sustainable development [Schmithüsen 2008]. Such sustainable development requires that forests maintain their structure and ecosystem functioning despite disturbances (i.e., climate change) [Bebbington et al. 2018]. Therefore, the development of multi-functional forest management in the face of shocks is a key challenge for future resource management in Europe and worldwide [Bolte et al. 2010]. However, such an approach needs to be defined in a suitable systematic way that is able to combine the societal needs with its economic objectives.

1.1.3 Multi-functionality viewed as a set of complex social and ecological interactions

Nocentini et al. [2017] argue that multi-functional forest management has been first based on the “wake theory” which states that if forests are efficiently managed for wood production, then all other utilities will follow [Kennedy and Koch 2004]. Dynamics and interactions from other ecological and social systems tended to be underestimated and the consequences have often been, and still are, conflicts (e.g., between timber production, landscape and nature conservation, and recreation) [Mckercher 1992, Steinhäuber et al. 2015]. This calls for a systematic approach that combines the social and ecological facets focusing on the interactions that occur between them.

Often, ecological and social scientists have studied emergent forest ecological and social phenomena. However, in their domains, neither the natural nor the social sciences can explain how integrated human and ecological systems emerge and evolve because human and ecological factors work simultaneously at various levels [Alberti et al. 2003]. Moreover, over the past twenty-five years, science has witnessed an ontological shift in understanding human-nature relationships. As outlaid by Schoon and Leeuw [2015], variously called coupled natural-human systems, coupled human-environment systems, socio-environmental systems or social-ecological systems, all refer to common features found in the past scientific studies. Essential features encompass the idea that a concept of a social-ecological system (SES) represents an assimilation of analyzing and studying humans as an essential part of the environmental world. However, this assimilation focuses on the complexity exhibited within the interaction of the different integrated social and ecological components. The basic idea of SESs is to be explicit in linking together the ‘human system’ (e.g., communities, society, economy) and the ‘natural system’ (e.g., ecosystems) in a two-way feedback relationship [Berkes et al. 2014]. This integration of humans in nature is important because, in any conservation effort, there are interactions and ‘feedback’ between ecological (biophysical) and social (human) subsystems. This includes essential links related to people’s knowledge (e.g., local or traditional knowledge), and management institutions, as well as ‘rules’ and ‘norms’ that mediate how humans interact with the environment.

Globally, forests have been increasingly seen as social-ecological systems [Nagendra 2007, Fleischman et al. 2010, Oberlack et al. 2015, Vogt et al. 2015]. In particular, humans not only benefit from forests but impact and shape their capacity to generate functions [Folke et al. 2005], creating a dynamic mutual and reciprocal relationship between humans and forest ecosystems [Mung’ong’o 2009] which alters their capabilities to continue providing many of their functions [MEA 2005]. These interactions can be understood to exist within socio-ecological systems where management requires sustained and coordinated responses by policy-makers [Halliday and Glaser 2011]. This is because of the complex interlinked nature of social and ecological systems [Erb et al. 2009, Figueiredo and Pereira 2011, Young et al. 2006], which cannot be understood if the two systems are approached independently [Figueiredo and Pereira 2011]. For these reasons, an SES lens is crucial.

In this vein, when considering forests as complex systems [Messier et al. 2015] with multiple economic and social components, the concept of multi-functionality changes from a set of different outputs to a set of complex social and ecological interactions [Nocentini et al. 2017]. Therefore, to better integrate multi-functional forest management, there is a need to systematically understand interactions between social and ecological systems inside the forest complex system. Notably, forest ecosystems are increasingly viewed as complex social-ecological systems (SESs) requiring multi-functional management.

1.1.4 Infrastructures as mediation for forest social and ecological interactions

Infrastructure systems have traditionally been designed to manage (and in some cases control) environmental systems and ensure that critical services and resources are available where and when they are needed [McPhee 1989]. For example, irrigation systems have been constructed to provide water to agricultural areas which help to grow agricultural crops, maintain landscapes, and revegetate disturbed soils in dry areas and during periods of less than average rainfall. Likewise, forest regrowth has been associated with the presence of robust community institutions and co-management between communities and the national government [Oberlack et al. 2015]. Similarly, the robustness of urban systems to natural hazards often depends on engineered structures such as levees, roads, or buildings [Yu et al. 2014]. Many social-ecological systems (SESs), including mountain forests, depend heavily on infrastructure. How such critical infrastructure mediates social and environmental interactions is thus central to many pressing sustainability challenges in SESs [Anderies et al. 2004].

Thinking in terms of infrastructure has been widely practiced in literature [Frischmann 2005, Kamran and Shivakoti 2014, Muneepeerakul and Anderies 2017]. Recent works analyze the ways in which the special nature of infrastructures affects both, how it is provided and its impact on the economic activities [Anderies et al. 2016]. For example, Frischmann [2005] builds on the idea that some resources are "inherently public" [Rose 1986] and develops a model of infrastructure that he uses to articulate why certain resources he classifies as nontraditional infrastructure (i.e. environmental and intellectual infrastructures) ought to be managed in a "… openly accessible manner". In view of this, infrastructures are broadly defined to include natural and human-made infrastructures (both physical and social) that enable the operation of society. Essential to this argument is thinking carefully about the many ways infrastructures generate difficult-to-observe spillovers that, in turn, generate value to society. In fact, Anderies et al. [2016] argue that "not considering these values may distort institutional analysis by placing too much emphasis on the problem of providing infrastructure while neglecting the importance of the demand for the many values infrastructures may provide". For instance, Muneepeerakul and Anderies [2017] discuss the fact that spillovers from fundamental biophysical and social features play an important role in reducing high transaction costs, thus enabling effective governance regimes capable of addressing diverse emerging problems, rendering "governance" as a spillover from the operation of the system.

Following this rationale, the relation between multi-functional forest use as well as the capacity for forest production can be highlighted with the concept of infrastructures [Bizikova et al. 2012, Yu et al. 2015]. Understanding how such infrastructures mediate the interaction between human functions in the natural environment helps confront questions of management application (i.e. irrigation canal designs, Martin and Yoder 1987; reforestation, Bray 2009) and consequently improve forest sustainability. With that in mind, the commonly used term "social-ecological systems" typically emphasizes the interaction between a set of infrastructures related to social and ecological processes [Frischmann 2007, 2012, Anderies et al. 2016].

This rationalization subjugates forests to sustainability established on the understanding of SES concepts. However, the sustainability approach is difficult to operationalize in any meaningful sense in an SES context for a range of reasons [Anderies et al. 2013, Benton et al. 2018]. To this end, it is important to compel sustainability to be practical based on an understanding that starts from the concepts of SES.

1.1.5 Operationalizing sustainability with integrative tools

For forests incorporating complex dynamics with inner-functional trade-offs, uncertainty and controversy over the best management strategy arises from a constantly changing physical and social environment (i.e., climate change and changing social values). How will forest ecosystems respond to infrastructure management strategies? What is the best way of meeting management objectives? Are these objectives consistent with societal goals? We do not have all these answers, but instead, we adapt. Under such circumstances, designing and adopting more sustainable ways of natural resource use, in rehabilitating degraded ecosystems, and in providing adequate legal and policy measures is imperative.

Moreover, there is often a lack of sound knowledge of viable alternatives for the current use of forest ecosystems. Adaptive management can help forest governments operate in the face of uncertainty, learning from the effects of their infrastructure investments on resource quality and quantity (sustainability) and its links with ecosystem functioning at the same or larger scales. Only through expanding the knowledge base on the relationships between human activities and natural resources (including the relation with biodiversity and forest functioning), and through continuous experimentation and adaptation to cope with change, will a more sustainable use of forest resources come within reach.

1.2 Tools and concepts

1.2.1 SES framework as a tool to understand the forest's complex intra-functional interactions

Nonetheless, analyzing interactions between ecological and socio-economic components of forest ecosystems and consequences on its integrity calls for a multi-disciplinary framework that can provide a common language to understand emergent patterns of interactions [Ostrom et al. 2007, Liu et al. 2007, and Ostrom 2009]. Ostrom's SES framework [Ostrom 2009, McGinnis and Ostrom 2014] is useful for such analysis as it has been designed to be applied to different SESs that could range from lakes [Brock and Carpenter 2007] and irrigation systems [Cox 2014] to fisheries [Schlüter et al. 2014, Partelow et al. 2016, 2018] to forests [Nagendra 2007, Fleischman et al. 2010, Oberlack et al. 2015, Vogt et al. 2015].

Derived from the institutional analysis and development framework (IAD) [Kiser and Ostrom 1982], the SES framework is a particularly noteworthy addition to the set of frameworks, theories, and models used for the study of sustainability [Ostrom 2007, 2009]. This framework (figure 1) identifies the broad characteristics of the resource system, resource units, governance system, and actors that together affect the structure of an action situation leading to relevant interactions and outcomes, as well as being embedded in social, economic, and political settings with related ecosystems. Within each of these broad characteristics, there are second-tier variables, and frequently, third-, fourth-, and fifth-tier variables [Nagendra and Ostrom 2014]. This nested hierarchy of variables was not proposed with the intent to suggest that all variables are relevant to all the cases. Rather analysts might find the SES framework helpful as a diagnostic tool that enables them to define clearly the level of tier and its variable of interest and organize them into connected groups [McGinnis and Ostrom 2014].

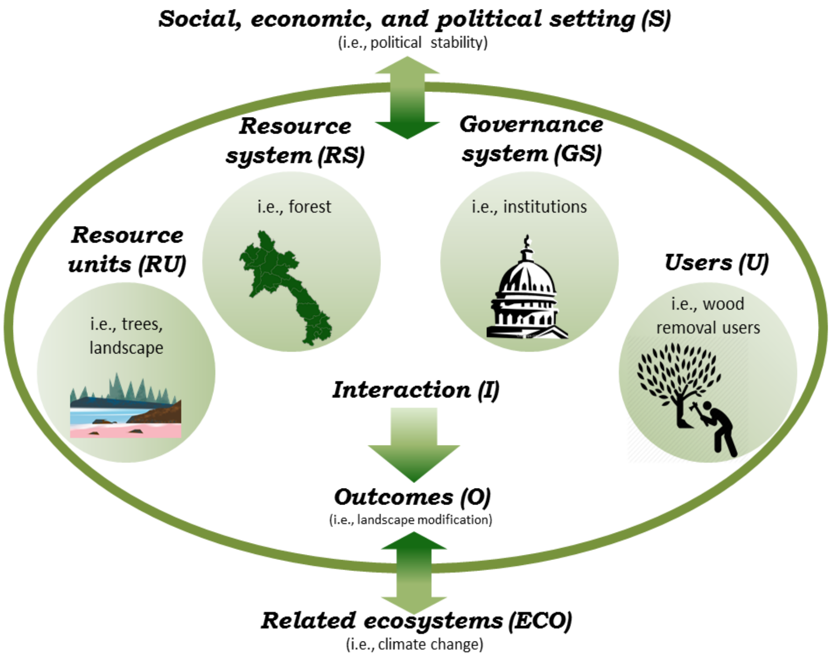


Figure 1. The social-ecological system framework as described in Ostrom [2009]. The 4 main components RS, GS, RU, and U that interact (I) to produce outcomes (O), while being embedded in a social, economic, and political settings (S) and related ecosystems (ECO). These 4 main components incorporate embedded second, third, etc, -tier variables, in which they introduce further analysis to the functionality of the SES.

In this context, when viewing forests as complex SESs, multi-functionality can be embedded in the SES framework within multiple tier variables, in which it can help provide a list of multi-tiered social and ecological variables that can generally be applied to describe variables in a complex system across cases. Nonetheless, for SESs incorporating a high dependency on infrastructures (in our case, mountain forests), there is a need for a focus, within the SES framework on how the special nature of infrastructures, and their provision, systematically impact the outcome of a multi-functional approach for management of forest ecosystem.

1.2.2 The robustness framework to characterize shared infrastructures

The robustness framework [Anderies et al. 2004] can be used to provide a systematic way of thinking that focuses on how different infrastructures interact in terms of the services they provide. By highlighting the key roles of infrastructures on socio-ecological interactions, this framework avoids artificial and potentially misleading distinctions between various systems. In particular, the robustness framework can be used to analyze the dynamics of the forests' SES. Figure (2) shows how the framework delineates four components of the SES (resource, resource users, public infrastructure, and public infrastructure providers), their interactions, and how these components and interactions influence the capacity of an SES to cope with internal and external disturbances.

As defined by Anderies et al. [2016], there are five main types of infrastructure considered by the framework: (1) hard infrastructures which are human-made infrastructures such as roads; (2) soft infrastructures, which are a collections of human-made "instructions" for using other type of infrastructures, such as institutional arrangements and decision making processes; (3) natural infrastructures, which are non-human made hard infrastructures critical for society (e.g., forests); (4) human infrastructures, which refer to knowledge; and (5) social infrastructures, which refer to the relationships we have with each other's. The framework explicitly recognizes the role of public infrastructures in influencing the system at the component level. Moreover, it clarifies the "configurable" nature of the system, i.e., a minimal set of infrastructure classes are required before interesting higher-level organizational patterns emerge (i.e., well-being, communities, societies, etc.). When thinking in terms of robustness framework, the question is not "what is the right policy or set of institutions for a particular problem or context?", but rather "what infrastructure can we influence that might nudge the system toward a robust configuration that produces a mass and information flow that is valued by society?" [Anderies et al. 2016]. The framework has been widely applied to analyze problems of fisheries [Barnett and Anderies 2014, Krupa et al. 2014], coastal systems [Homayounfar et al. 2018], irrigation systems [Cifdaloz et al. 2010], and has been qualitatively used in investigating the emergence of stable governance for SESs [Muneepeerakul and Anderies 2017] .

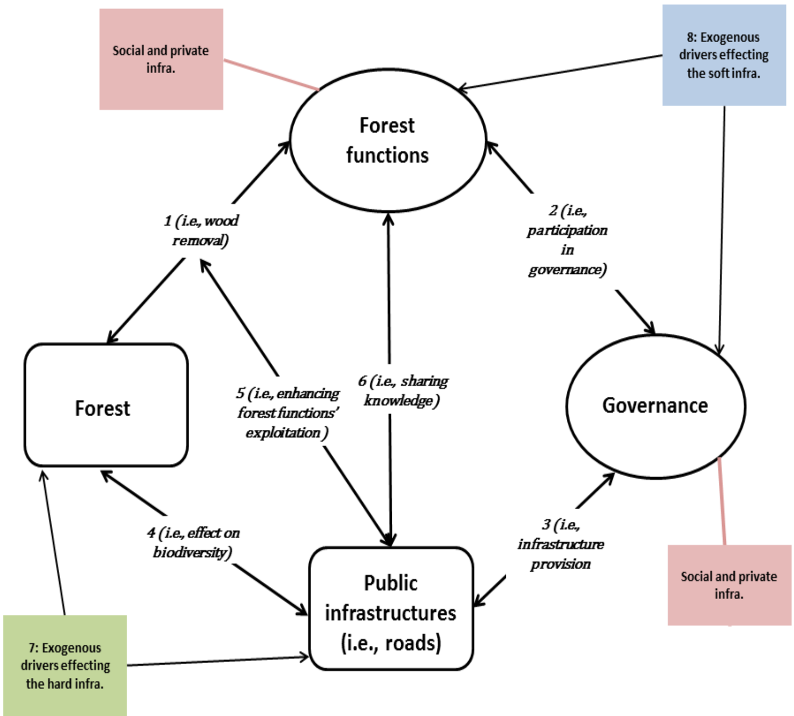


Figure 2. The conceptual model of the robustness framework introduced by Anderies et al. [2004] and adapted to forest multi-functional management. It specifies four generic components common to most of the forest in a multi-functional management context (forest, forest functions, Infrastructures, and governance as infrastructure provider), and their interactions (Link 1 to 6). It also describes the presence of external disturbances on ecological and social components (Links 7 and 8, respectively). Boxes refer to biophysical components of the system while circles refer to social ones.

As mentioned earlier, understanding how infrastructures mediate the interaction between forest functions in the natural environment helps confront questions of management application and consequently improve forest sustainability. However, infrastructure design must comply with the principles of sustainable development. This requires, amongst other things, that this design must play a role in helping forests maintain their structure and ecosystem functioning despite disturbances (i.e., climate change). Therefore, a development, through infrastructure provision, of adaptive multifunctional forest management application in the face of shocks is a key challenge for future resource management in Europe and worldwide [Bolte et al. 2010].

1.2.3 From adaptive management…

Adaptive management is a systematic approach for improving resource management by learning from management outcomes [Sexton et al. 1999, Williams 2011]. Its origin can be traced back to ideas of scientific management pioneered by Frederick Taylor in the early 1900s [Haber 1964, Bormann et al 2006]. Various perspectives on adaptive management are rooted in parallel concepts found in business (total quality management and learning organizations [Senge 1990]), experimental science (hypothesis testing [Kuhn 1996]), systems theory (feedback control [Ashworth 1982]), and industrial ecology [Allenby 1994]. The concept has attracted attention as a means of linking learning with policy and implementation [Stankey et al. 2005, Szaro 1996]. Although the idea of learning from experience and modifying subsequent behavior in light of that experience has long been reported in the literature, the specific idea of adaptive management as a strategy for natural resource management can be traced to the seminal work of Holling [1978], Walters [1986], and Lee [1993].

Adaptive management as described here is infrequently implemented (e.g., Westgate et al. [2013]), even though many resource planning documents call for it and numerous resource managers refer to it [Elliott et al. 2004]. It is thought by many that merely by monitoring activities and occasionally changing them, one is doing adaptive management. Contrary to this commonly held belief, adaptive management is much more than simply tracking and changing management direction in the face of failed policies, and, in fact, such a tactic could actually be maladaptive [MacDonald et al. 1999]. An adaptive approach involves exploring alternative ways to meet management objectives, predicting the outcomes of alternatives based on the current state of knowledge, implementing one or more of these alternatives, monitoring to learn about the impacts of management actions, and then using the results to update knowledge and adjust management actions [Murray and Marmorek 2004].

A context for forest management involves a decision-making environment characterized by multiple (often competing) management objectives, constrained management authorities and capabilities, dynamic ecological and physical systems, and uncertain responses to management actions. Management thus involves not only predicting how ecological or physical systems are likely to respond to interventions, but also identifying what management control are available, what outcomes are desired, how much risk can be tolerated, and how best to choose among a set of alternative actions. The challenge confronting forest governments is to make “good” decisions in this complex environment, recognizing that the quality of decision making in the face of uncertainty should be judged by the decision-making process as well as progress towards desired outcomes.

A common problem in natural resources management involves a temporal sequence of decisions, in which the best action at each decision point depends on the state of the managed system. Because management actions at each point in time can influence change in the resource system from that time forward, the goal of management is to prescribe objective-driven strategies that account for both the current and future impacts of decisions. A key issue is how best to choose management actions, recognizing that the most appropriate management strategy is obscured by limited understanding [William and Brown 2016].

Often the uncertainty about forest multi-functional management impacts is expressed as disagreements among diverse functions that are related to different views about the direction and magnitude of resource change in response to management. An adaptive approach explicitly articulates these viewpoints, incorporates them into the decision-making process, and uses management itself to help identify the most appropriate view about resource dynamics. In other words, the adaptive management concept incorporates research into action [Gosselin et al. 2018].

Mobilizing such a definition of adaptive management opens the door for specifying and characterizing environmental and social constraints that can define stable states for forest environmental systems.

1.2.4 …To safe operating space

The "safe operating space" for humanity concept provided through the planetary boundary framework [Steffen et al. 2015, Rockström et al. 2009] has gained much attention. In brief, Rockström et al. [2009] used the theory of critical transitions [Scheffer et al. 2001] to define the modern boundaries for Earth system biophysical state variables, using the Holocene (the last 11,000 years) as a baseline period. Exceeding the boundaries takes the Earth beyond the "safe operating space" (SOS) where the risk of unpredictable and damaging changes to social-ecological systems becomes very high.

Raworth [2012] introduced the 'doughnut' concept (figure 3) in order to locate social concerns within the original safe operating concept, where human wellbeing is deprived if it falls below defined social foundations for basic needs (e.g., food, gender equality, health).

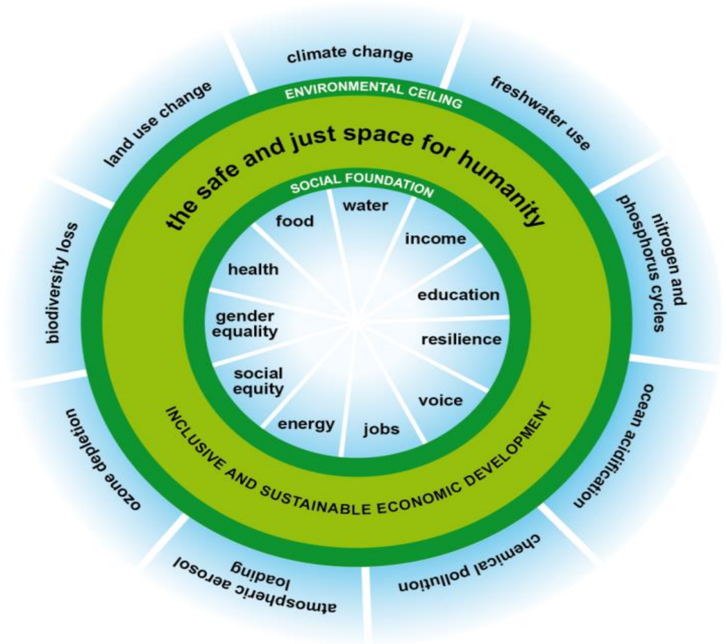


Figure 3. Planetary and social boundaries: a safe and just space for humanity [Raworth 2012]. The figure illustrates the critical processes (i.e., biodiversity, freshwater, climate change, etc.) that keep the planet in a stable state. Just as there is an environmental ceiling, beyond which lies unacceptable environmental degradation, so too there is a social foundation, below which lies unacceptable human deprivation (i.e., food, water, health, etc.).

In particular, this concept of SOS is based on acknowledging that the impact of human activities on the earth system has reached a scale where abrupt global environmental change can no longer be excluded. This is why scientists refer to a new geological era called Anthropocene, which replaces the relatively stable Holocene conditions. The authors proposed a new approach to global sustainability in which they "define planetary boundaries within which we expect that humanity can operate safely" [Rockström et al. 2009].

However, in an attempt to study SOSs at the regional scale, a recent study [Hossain et al. 2017] acknowledged the cross-scale issues that remain because of the many planetary boundaries that are aggregated from regional-scale problems, such as land and freshwater uses [Blomqvist et al. 2012, Lewis 2012]. Critical transitions can occur within biophysical and social systems singly or combined and at any scale [Scheffer et al. 2001], and setting a boundary at a global scale does not necessarily help to inform policy at a regional scale. Therefore, Dearing et al. [2014] proposed a methodology to downscale the safe operating space and 'doughnut' concepts to the regional scale. In brief, they defined the safe operating space as the gap between an environmental ceiling defined using empirical dynamical properties (e.g., envelope of variability, early warning signals) of ecological variables and a social foundation defined from minimum norms of human outcomes (e.g., health).

Therefore, such a concept can be introduced to the management of SESs, including forests. Building on this, forest sustainability implies the existence of ecological boundaries that allow the environment to be maintained, as well as the presence of minimal societal needs that are important to be met. Such implication calls upon tools that are able to translate this concept of SOS into practical means. In this vein, the viability theory [Aubin 1991] may be helpful for defining constraints and boundaries and analyzing tipping points in a dynamical tone.

1.2.5 Viability theory for using adaptive management to assess SOSs

The main purpose of viability theory [Aubin 1991] is to explain the evolution of the state of a control system, governed by non-deterministic dynamics and subjected to viability constraints, to reveal the concealed feedbacks that allow the system to be regulated and provide selection mechanisms for implementing them. It assumes implicitly an "opportunistic" and "conservative" behavior of the system: a behavior that enables the system to keep viable solutions as long as it's potential for exploration (or its lack of determinism) - described by the availability of several evolutions - makes possible their regulation.

Viability theory is described as a mathematical theory based on three main features, namely: (i) non-determinism of evolutions, (ii) viability constraints, and (iii) inertia principle. The two first features concern the state trajectory of the studied system and reflect the fact that a system can evolve in many different and possibly unpredictable ways depending on its initial state, its past evolution, the environment in which it evolves or anything else (non-determinism), and also the fact that, for many reasons, the evolution of a system is restrained by some constraints that must be satisfied at each instant of time. These are the two founding pillars of viability theory models. The last feature (inertia principle) concerns the control variables and stipulates that these controls are changed only when required for maintaining viability. The system is considered not viable if the choice of control does not allow it to be maintained in the domain of constraints. To find a viable solution (or a set of viable solutions), viability theory follows a backward (or inverse) method, that is, starting from a set of given viability constraints, one looks for the set of initial states from which the system can be indefinitely viable. In general, in deterministic cases, a lot of different control strategies are possible for maintaining the system in the constrained domain, which is the difference with the optimal control approach that proposes to find an optimal unique solution.

As mentioned before, in the viability framework, an important innovation is to introduce controls to explicitly account for the possibility to act on the system: controls are not fixed beforehand. Indeed, the purpose is to find suitable strategies that will maintain indefinitely the properties of the dynamical system within K. In discrete-time, this means that at each time step, there is a set of possible controls that one must choose from. A dynamical deterministic control system can be written, in discrete time, as follows:

$$\forall t \geq 0, x(t+dt) = x(t) + f(x(t), u\big(t, x(t)\big)dt$$

Where $x(t) \in X$ is the state of the system at instant t. The space of state X is a subspace of R^n, where n is the number of dimensions of the problem. At each time step, the dynamic f of the system depends on the control $u(t, x(t)) \in U(t, x)$. This control, taken at time t based on the state in which the system is found in, influences the dynamics at the next time step. The space of controls $U(t, x)$ is generally discretized belonging to a subspace of R^q where q is the number of discretized values of available controls.

We then define the set of constraints $K \in R^n$ in which we want to maintain the system. We will say that the evolution of the system is viable if:

$$\forall t \geq 0, x(t) \in K$$

The viability theory makes it possible to determine how to choose the actions at each moment in order to satisfy the constraints in a sustainable way. The major concept of this theory is the viability kernel. It is the set of initial states of the studied system for which there exists at least a sequence of controls maintaining the system in the constraint domain, up to a given time horizon. The viability kernel is written:

$$Viab(K) = \{x(0) \in X \; such \; that \; \exists u(.), \forall t \geq 0, x(t) \in K\}$$

Thus, if the initial state $x(0)$ of the system is not in this viability kernel, its output from the constraint domain is unavoidable. On the other hand, if its initial state is part of the viability kernel then there is a possibility of keeping the system in the constraint domain.

The viability kernel provides important information about the system being studied [Aubin 2002]. For example, if the kernel occupies the entire constraint space, regardless of the initial state of the system, we will have solutions to maintain its properties. On the other hand, if the kernel is empty, this implies that the current system is not viable as it is the case in [Domenech et al. 2011] and other management options need to be explored.

1.3 Objectives and organization of the thesis

The objective of this thesis aims to understand the interactions that happen within the forest's SES and address their complexities at the multi-functional management level with a focus on the role of infrastructures (see figure 4). This approach calls out tools that are able to deeply highlight the concept of social-ecological systems and the role of infrastructures. To do so, we use the well-known SES framework developed by Ostrom [2009] to examine the interactions that happen between the social and ecological structures that constitute its exploitation system. We base our work on the idea that the performance of forest functions is linked to the vacancy of infrastructures. In particular, we aim to link conceptually the multi-functional management of forests to the multi-functionality of infrastructures. To understand how infrastructures are mediated within the forest SES, we employ the robustness of coupled infrastructure system framework [Anderies et al. 2004, Anderies et al. 2016] adopting its concepts and definitions.

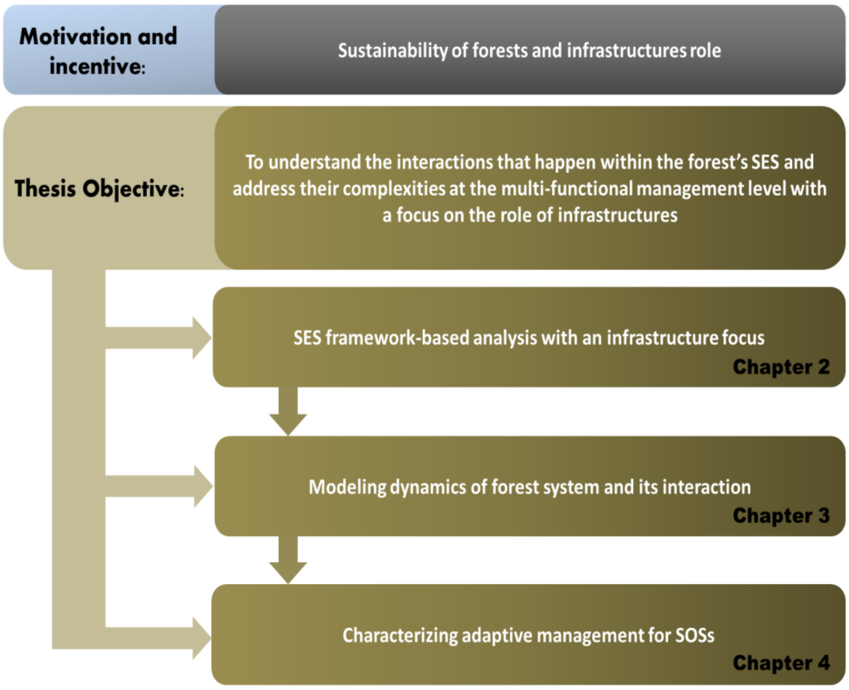


Figure 4. Conceptual figure showing the different objectives of the thesis. The objectives are divided into two parts, qualitative and quantitative parts. The qualitative part deals with applying an SES-based analysis to the multi-functional management of forests. Based on this, the quantitative part deals with conceptually developing a mathematical model where we apply viability theory to explore the extent of infrastructure adaptive management strategies to maintain SOSs for multi-functional management.

The theoretical foundations of this thesis lie in the idea of combining the SES and robustness frameworks to represent complexities and interactions within SESs that depend heavily on infrastructures. The core idea is represented with the ability of the robustness framework to conceptually represent the complex link between Interactions (I) and Outcomes (O) found in the SES framework, in which it focuses on how infrastructures mediate interactions between the SES components. For that, **Chapter 2** of this manuscript aims to analyze the forest SES through a complementary application of the SES and robustness frameworks. The ultimate goal is to be able to address three key issues: (1) to characterize functional system with a focus on the infrastructure role, (2) to describe the governance (infrastructure providers) revolving around forest multi-functional management, and (3) to provide a conceptual approach that visualizes the multiple tier effect of investments in infrastructures (including effects on forest functions). These goals opens a door towards using a mathematical approach to model the effects (trade-offs and synergies) that can occur between forest functions.

As mentioned before, we seek to mathematically model our acquired understanding of the multi-functional forest management (conducted qualitative analysis, **Chapter 2**). To fully integrate the role of shared infrastructures and their governance into ecosystem science, **Chapter 3** proposes a generic conceptual modeling approach. We explore and analyze the consequences of infrastructure alignment decisions on the performance of forest multi-functional management. The idea is to induce the non-linear behavior of infrastructures with the dynamical process of a model (you either use infrastructure, or you do not). We inspect the impact of the concept of spillovers on forest management, which links the multi-functionality approach in SESs to the multi-functionality of infrastructures.

As explained earlier, the sustainability of forests is an issue of paramount importance, and policymakers seek to understand what it means, practically and conceptually, to be sustainable. In the presence of problems and obstacles that emerge from a lack of data from and partial knowledge of forest ecosystems, adaptive management can be a useful strategy for withstanding shocks and disturbances that enhances the sustainability of the resource. For that, viability theory can be used to answer questions about the robustness and sustainability of systems and can be used to determine sustainable policies for their management. To characterize adaptive management strategies, **Chapter 4** explores the application of viability theory to the model developed in **Chapter 3**, where we focus our study and analysis on controls that concern the infrastructure provisions and analyze their effect on the performance of the multi-functional forest management.

A social-ecological system analysis

2.1 A social-ecological system analysis

The introduction has framed the rationale that this thesis is based upon. This rationale is motivated by the conceptual and qualitative understanding of interactions within forest SESs. The insights of investigation on how multi-functional forest management can be framed and analyzed are highlighted through the understanding of the functionality of the SES. To understand the performance of multiple forest functions (or production systems), we need to consider the role of infrastructures in affecting the outcomes of their management strategies.

This article presents a novel infrastructure perspective that explains how different infrastructures of the SES interact to produce diverse functions of the forest. To do so, we use the description power of Ostrom's SES framework [Ostrom 2009, McGinnis and Ostrom 2014] to identify general variables of the system and their interactions without specifically referring to their consequences on collective action theory; we then apply it to a specific mountain forest case study (Quatre-Montagne forest, Vercors region, France). Particular to the case study, infrastructures play an important role in mediating how different parts of the system interact. For example, forest manager's timber exploitation is limited by their use of public infrastructures (roads). Consequently, we connect variables of the SES framework analysis to their relative infrastructures. Finally, we use the robustness framework as a tool to understand the connection between underpinned infrastructures. We present multiple forest functions through the lens of the framework by applying it at each function. We combine and use the SES and robustness framework, with a complimentary application, to explain institutional arrangements behind multi-functional management practice.

2.2 Presentation and contribution of the article

This article has been submitted to *Ecology & Society* journal, pending revisions. Its principal contributions are the following:

- To implement a complementary application of the SES and robustness frameworks to conceptually understand interactions and complexities that occur in an infrastructure mediated multi-functional forest;

- To conceptually describe the governance that revolves around multi-functional forest;

- To present conceptual insights investing in function-specific infrastructures to augment the performance of multi-functional forest management taking advantage of the concept of "infrastructure spillovers".

2.3 Conclusions

The methodology followed in this article has opened a prospective for a direct link between the SES and robustness frameworks. This link is illustrated in the ability of the robustness framework to conceptually describe the complex relationship between Interaction (I) and Outcomes (O) found in the SES framework in the case of SESs that depend heavily on infrastructures. This work can thus be useful for deriving conclusions for governance of SESs. The methodological nature of this paper has been applied to the Quatre-Montagne forest in order to facilitate the comprehension of the approach. Although we have chosen in this paper a forest case study to highlight the multi-functionality concept, we mention that this concept has recently gained fame within other managed ecosystems (rivers, streams, and lakes [Podolak 2012, Munch et al. 2016, Habersack et al. 2018] and, agricultural systems [Ricart et al. 2019], fisheries [Mulazzani et al. 2019]). This can open the door toward the inauguration of the multi-functionality concept within existing SES frameworks.

The analysis can open the door for developing operational tools that can help to better devise multi-functional management strategies taking into account the social and ecological aspects of an SES. One example of such use of the framework can be found in the paper written by Muneepeerakul and Anderies [2017], in which the authors operationalize the framework's conceptual map to build up a mathematical model that explores the circumstances of the emergence of stable governance. In the same vein, **Chapter 3** seeks to model the role of infrastructures and their provision on the performance of multifunctional forest management

2.4 Text of the article

Which infrastructures for which forest function? Analyzing the multi-functionality through the social-ecological system framework

Mojtaba HOUBALLAH[1], Jean-Denis MATHIAS[1], Thomas CORDONNIER[2]

[1] UR LISC, Laboratoire d'Ingénierie pour les Systémes Complexes, IRSTEA, 9 Avenue Blaise Pascal, CS 20085, 63178.

[2] Univ. Grenoble alpes, IRSTEA, UR LESSEM, Domaine universitaire, 2 rue de la Papeterie, BP 76, 38402 St-Martin-d'Héres Cedex, France.

Abstract

Landscapes are subjected to ecological and socio-economic forces of change, interacting in complex ways. To cope with these changes, landscape planning of natural resource management consists of integrating socio-cultural, ecological, and economic considerations in an analytic and systemic way. In this vein, social-ecological systems (SES) frameworks have been developed to help in analyzing key factors that derive the dynamics of such complex adaptive systems. For forests, multifunctional management, which also highlights the ecological and the socio-economic roles of forests for society, has become a central objective for several European countries (e.g., France, Italy, and Germany). However, further development of methods, tools, and conceptual approaches is needed to enable us to understand the arrangements behind management practices that include complex human and environment interaction. This study adopts Ostrom's SES framework and Anderies robustness framework to highlight how forestry institutions affect forest ecosystems, forest functions, and social arrangements. As an illustration, we apply both frameworks to the Quatre-Montagne forest, located in the South-East of France, where multi-functionality is a major objective of forest governance. We first apply the SES framework to construct an analysis of the Quatre-Montagne forest specifying the first-tier and second-tier variables. From this, we describe the importance of variables related to infrastructures in shaping the interactions between components of the SES. We then apply the robustness framework, developed by Anderies, because we believe that the robustness framework better enables the analysis of ecosystem functions to infrastructure governance than the SES framework which provides a better descriptive capacity of the variables. We discuss insights, based on our infrastructure analysis, which can be used when establishing management design for efficient forest management with heavy infrastructure dependencies.

Key Words: Forestry; forest accessibility; multi-functionality; infrastructures; robustness theory; social-ecological systems;

INTRODUCTION

Forests provide a large number of provisioning, regulating, supporting and cultural functions that stabilize climate, protect plants and animal species, provide food and shelter to local communities, protect critical human infrastructure such as settlements, roads, and railway lines from gravitational natural hazards, and isolate large amounts of carbon as a result of recycling of gases [Nasi et al. 2002, Millenium ecosystem assessment 2005, Bonan 2008, Gamfeldt et al. 2013]. The ideal concept of maintaining a continuous flow of goods and services from the forest has occupied a central place in forestry thinking [Ciancio and Nocentini 1997, Puettmann et al. 2009]. Meanwhile, there is a raising awareness that managed ecosystems are characterized by complex dynamics with high uncertainty related to rapid environmental and socio-economic changes [Benson and Craig 2014]. Forestry is facing a challenge that consists in achieving sustainability in a changing environment with better integration of interaction between ecological and social systems [Von Detten 2011].

Analyzing interactions between ecological and socio-economic components of forest ecosystems and consequences on their integrity calls for a multidisciplinary framework that can provide a common language to understand emergent patterns of interactions [Ostrom et al. 2007, Liu et al. 2007, and Ostrom 2009]. Ostrom's social-ecological system (SES) framework [Ostrom 2009, McGinnis and Ostrom 2014] is useful for such analysis as it has been designed to be applied to different SESs that could range from lakes [Brock and Carpenter 2007] and irrigation systems [Cox 2014] to fisheries [Schlüter et al. 2014, Partelow et al. 2016, 2018] to forests [Nagendra 2007, Fleischman et al. 2010, Oberlack et al. 2015, Vogt et al. 2015]. Additionally, recent examples show that societal preferences and values can change remarkably in a relatively short period thoroughly changing the social environment for forest management [Johnson and Swanson 2009, Seidl and Lexer 2013]. Adaptation strategies to changing uses and values of forests need to be implemented in order to sustain the provisioning of multiple forest functions under changing future conditions [Spiecker 2003, Koskela et al. 2007]. In this context, forests are complex SESs requiring adaptive and multifunctional management.

Forest multifunctional management, which also highlights the ecological and economic roles of forest ecosystems for society, has become a central objective for several European countries (e.g., France, Italy, and Germany) [Slee 2012]. In this vein, multifunctional forest management practice is defined as a land-use strategy capable of meeting divergent societal interests, supporting forestry practices adaptable to different social groups, and remaining consistent with the principles of sustainable development [Schmithüsen 2008]. Nocentini et al. [2017] argue that such management has been first based on the "wake theory" which states that if forests are efficiently managed for wood production, then all other forest utilities will follow [Kennedy and Koch 2004]. Dynamics and interactions from other ecological and social systems tended to be underestimated and the consequences have often been, and still are, conflicts (e.g., between timber production, landscape and nature conservation, and recreation) [Mckercher 1992, Steinhäußer et al. 2015]. When considering forests as adaptive complex systems [Messier et al. 2013] with multiple economic and social components, the concept of multifunctionality changes from a set of different outputs to a set of complex interactions [Nocentini et al. 2017]. Therefore, and to better integrate multifunctional forest management, there is a need to systematically understand interactions between the social and the ecological systems in the forest. In this context, multifunctionality can be embedded in the SES framework within multiple tier variables, in which it can help provide a list of multi-tiered social and ecological variables that can generally be applied to describe variables in a complex system and in a way across cases.

Nonetheless, the relation between multifunctional forest use as well as the capacity for forest production is highlighted with the concept of infrastructures [Bizikova et al. 2012, Yu et al. 2015]. Understanding how such infrastructures mediate the interaction between human functions in the natural environment helps confront questions of management application and consequently improve forest sustainability. In view of this, infrastructures are broadly defined to include natural and human-made infrastructures (both physical and social) that enable the operation of society. With that in mind, the commonly used term “social-ecological systems” typically emphasizes the interaction between a set of infrastructures related to social and ecological processes [Frischmann 2007, 2012, Anderies et al. 2016]. SESs, such as forests, often exhibit non-linear dynamics as the rules of local interaction changes over time [Levin 1998]. Humans act alone on components of the system attempting to adapt, to change, or to transform the system when existing interactions can no longer be supported by its components [Walker et al. 2004]. Following an understanding of the relevant variables in the case study with the SES framework, we use Anderies’ [2004] robustness framework to conduct an institutional analysis examining how dimensions of governance and social organizations influence, adapt to and change the interdependencies between social and ecological variables described. Ideally, the framework can be used to provide a systematic way of thinking that focuses on how infrastructures interact in terms of the functions they provide.

In this article, we investigate how multifunctional forest management can be framed and analyzed through understanding the functionality of the forest SES. In particular, we present a novel infrastructure perspective that explains how different infrastructures of the SES interact to produce diverse functions of the forest. To do so, we use the descriptive power of Ostrom’s SES framework [Ostrom 2009, McGinnis and Ostrom 2014] to identify general variables of the system and their interactions without specifically referring to their consequences on collective action theory; we then apply it to a mountain forest case study (Quatre-Montagne forest, Vercors region, France). Particular to the case study, infrastructures play an important role in mediating how different parts of the system interact. For example, forest manager’s timber exploitation is limited by their use of public infrastructures (roads). Consequently, we connect variables of the SES framework analysis to their relative infrastructures. Finally, we use the robustness framework as a tool to understand the connection between underpinned infrastructures. We present multiple forest functions through the lens of the framework by applying it at each function. We combine and use the two frameworks mentioned (SES and robustness frameworks), with a complimentary application, to explain the institutional arrangement behind multifunctional management practice. This presentation of the robustness framework application conceptually highlights the link between Interactions (I) and Outcomes (O) within the SES framework variables (that will be introduced later). Indeed, we are certainly not the first people to think in terms of connecting two approaches to study, analyze, and understand complexities of SESs, for example, Partelow and Winkler [2016] interlinks the SES framework with the ecosystem services approach by applying them to the same case study, while Ban et al. [2015] associates concepts of ecosystem services, goods, and property rights with the SES framework.

The insight of the frameworks' application provides a more conceptually-integrated view of the forest functions by connecting them through social and physical infrastructures. As a result, when viewing each function from the lens of the robustness framework along with outlining related infrastructures and keeping in mind that there are common infrastructures for different functions, a systematic link can be identified between the concept of multifunctional forest management and multi-functionality of different types of infrastructures. The proposed frameworks' application does not only allow us to highlight interactions and conflicts between forest functions but also, helps in addressing them through identifying infrastructures that underpin these interactions. Our ultimate goal is to be able to address three key issues: (1) to characterize functional system, (2) to describe the governance (infrastructure providers) revolving around forest multi-functional management, and (3) to provide a conceptual approach that visualizes the multiple tier effect of investments in infrastructures (including effects on forest functions).

CASE STUDY

The Vercors regional natural park (VRNP) is a 206,000 ha area located at the border between the Northern and Southern French Alps (Fig. 1). 139,000 hectares of VRNP are dominated by forestland, with altitudes varying from 180 m to 2453 m. The main tree species are Silver Fir, European Beech, and Norway Spruce especially present in the Quatre-Montagne area. A mosaic of stand types with different tree sizes and varying species richness is now present. At low elevations, the forests are dominated by old simple coppices or mixed coppice and high forest and are generally composed of broadleaved species and silver fir standards. These forests have been mostly shaped by the heterogeneous mountain topography and a long history of human intervention. During the 19th century, almost all forests were intensively exploited for firewood, which favored beech coppices. Since the early 20th century, they have been progressively converted into mixed high forests, sometimes through conifer plantation but often by natural regeneration of local coniferous species. Approximately half of these forests are public [Gonzales-redin et al. 2015] and the rest is in the hands of private stakeholders. The particular case study selected for this research focuses on 25,000 ha (12% of the total area) located at the North of Vercors regional natural park, in an area known as 'Quatre-Montagne'. Figure (1) shows the Quatre-Montagne region within the Regional Natural Park (PNR) in the French Alps, (in dark green, public forests). The area is a part of the Grenoble agglomeration with implications for the impacts of tourism.

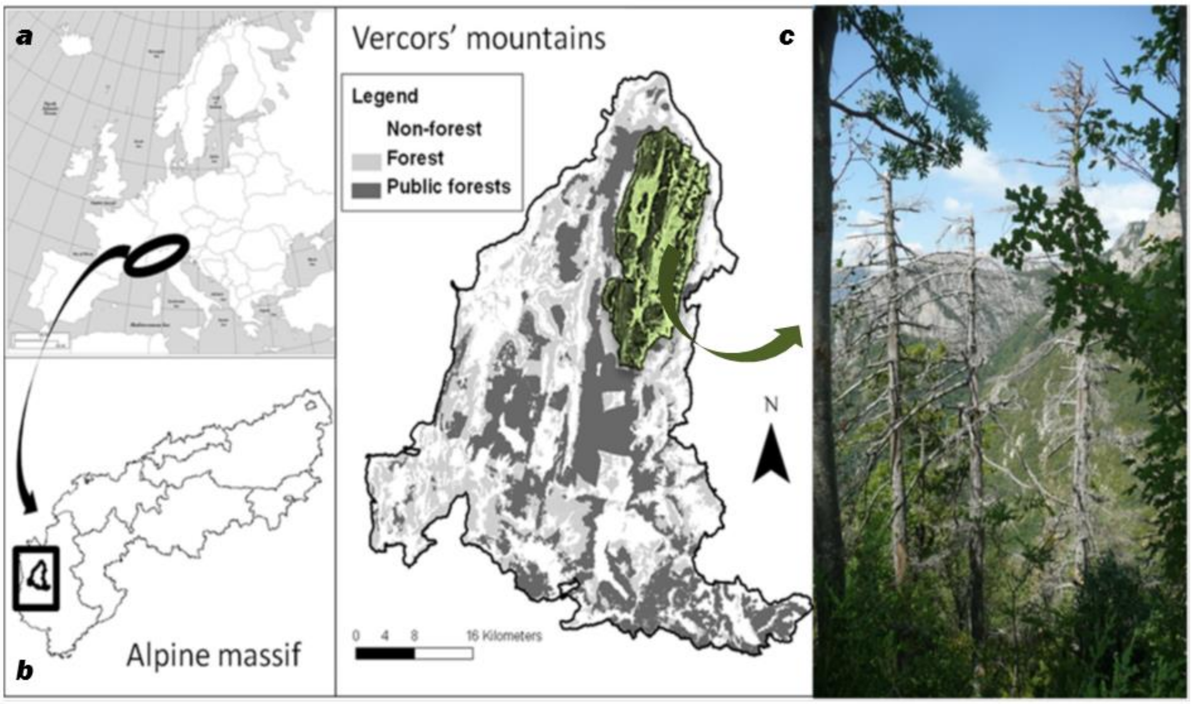
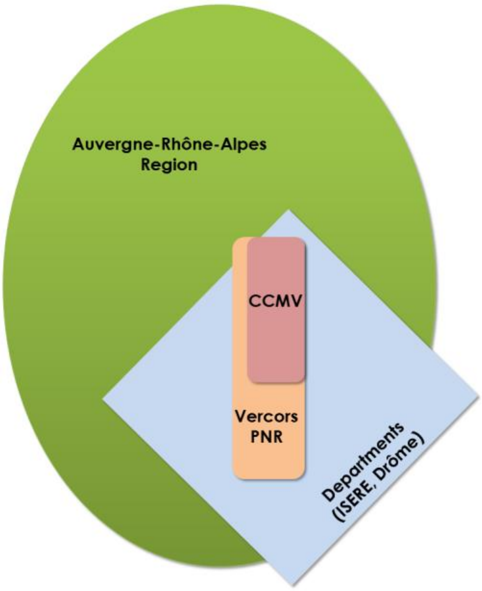


Figure 1. Study area location in the Alpine Mountain Range and the site of 'Quatre Montagne' (green area) at the north of Vercors Regional Park (VRNP), French Alps [Parmentier et al. 2013]. Panel (a) represents the location of the Alpine massif in the Europe continent. Panel (b) represents the Vercors Regional Park (VRNP) location in the Alpine massif. Panel (c) represents the location of the study area location site "Quatre-Montagne" (green area) as well as it shows non-forested (white), forested (light grey) areas inside the Vercors. Moreover, panel (c) also shows public forest areas within the Vercors' mountains (dark grey)

In accordance with the principles of preserving biodiversity and reducing gas emission (adapted from the earth summit in Rio de Janeiro 1992), the law on forest orientation [2001] recognized the multi-functionality of the forest. Alpine countries support the contribution of the forest to the sustainable development of their territory [Onida 2009, Avocat et al. 2012]. The general environment forum and the council of forests led to the adoption of a protocol of understanding among forest managers: to produce more wood while still preserving the biodiversity by favoring a territorial approach concerted in the framework of multifunctional forest management. In the Vercors, nature conservation plays an important role and even though multifunctionality is considered as essential with wood production, biodiversity and recreation are being consolidated at all scales [FORGECO 2014, Sarvasova et al. 2014, ARANGE 2015, Bugmann et al. 2017]. Moreover, the nature of topography and the landscape of the forest infer an obstacle as 36% of the forest is inaccessible and not exploitable for timber users [FORGECO 2014].

Forest governance in the Vercors is composed of three levels (see figure 2); region, department, and communes. The region develops its own strategy and supports territorial projects (for example the regional strategy for economic development and innovation (SRDEI) and sustainable development contracts with territory projects (CDDRA)) with the objective of mobilizing wood in the area and limiting gas emissions. The departments aim to reinforce rural/urban environment by developing their own strategies and supporting territorial projects (for example, developing agriculture strategic plans). The communes, considered as owners of public forests, promote wood production in the area and, in addition, lay grounds for the forest territory charters (Chartes Forestiers de Territoire, CFT in French) and execute operational expression of the different guidance documents that impact the territory. Specifically, the CFT represents a new flexible structure of local governance specific to France. The charts were introduced by the Law on forest orientation [2001] as an instrument of sustainable development of rural territories through the inclusion of advantages brought by forests into their economic, social and cultural environment and multifunctionality of forests. Being based on stakeholders' participation, CFT is entirely in line with governance implanting participatory mechanisms, decentralization, and empowerment of regional and local government, increasing the role of local communities and secure land-tenure arrangements [Kouplevatskaya-Buttoud 2009]. Following the European priorities, the CFT institutionalization aim is to integrate the forest as a core territorial policy together with other major issues such as the development of tourism and water management.



Territory	Description	Example of documents concerning exploitation activities	Example of Objectives
Auvergne-Rhône-Alpes Region	Administrative Region, develops their own regional strategies and support territorial projects	Simple management plan (PSG), regional ecological coherence scheme, sustainable development contracts with projects territories	Mobilize wood under exploitation/limit greenhouse gases
Departments (ISERE, Drôme)	Administrative department	Departmental Agricultural strategic Plan, exploitation projects and rural development	To reinforce Rural/urban-Environment Multifunctionality
Communes (CCMV)	Intercommunal territory near the Grenoble agglomeration	Territory Forest Charters, Operational expression of the different guidance documents that impact the territory	Develop/promote wood production

Figure 2. Schema representing the different entities involved in the governance of the forest. Orange rectangle represents the Vercors regional natural park (PNR) where it is partly governed by three entities. Regional governance which is represented by a green circle and its administration occupy all the PNR. Departmental governance represented by a light blue square where the jurisdiction resides almost on all the PNR. Communal governance represented by a pink rectangle inside the PNR. Although the jurisdiction overlaps, the three entities share different objectives and authority in the Vercors.

DATA COLLECTION AND ASSESSMENT

An examination has been conducted on studies and literature produced by the ARANGE [2011] and FORGECO [2014] projects that worked extensively on social, economic, and ecological data extraction of several case studies across Europe, with implication to the comparison of the case studies found in the ARANGE project. This precise examination is based on identification of information that is closely related to SES framework variables, defined in the next section. Moreover, a systematic review of peer-reviewed literature was conducted from the scholarly databases found in Scopus. Searches were conducted (as of January 2017) to find literature directly engaged with the Quatre-Montagne forest. In particular, we focused our search on literature concerning the performance of functions (wood production, tourism, and nature conservation), important stakeholders' conflict, and problems facing these conflicts. Search strings were guided by an extensive list of search terms (English and French terms) related to "Wood production", "Tourism", "Nature conservation", and "conflicts" with all terms tied with "Quatre-Montagne forest" and "Vercors forest". In addition to the literature issued by the projects (ARANGE and FORGECO), the search resulted in a total of 15 articles and reports (table S1, appendix). Each article and report was read, evaluated and coded with standardized criteria by the authors. Consensus coding was reached on the following categories for each article: source, type of the study, year of publication, and tone in which the assessment was done. The data assessment was built depending on what language made the most sense for each variable in which the determination of importance was qualitatively estimated by three levels: "strong", "moderate", and "low". This determination is done with comparison to other European mountain forests assessed by the ARANGE project. For a detailed explanation of the method used for data collection and assessment method, we refer the reader to the appendix.

SES FRAMEWORK ANALYSIS

The SES framework [Ostrom 2009, McGinnis and Ostrom 2014] identifies the broad characteristics of the Resource System and related Resource Units, Governance Systems, and Actors that together affect the structure of Action Situations leading to Interactions and Outcomes, as well as being embedded in Social, Economic, and Political Settings, and with Related Ecosystems (see figure 3) [Hinkel et al. 2014]. Within each of these broad characteristics, there are second-tier variables, and frequently, third-, fourth- and fifth-tier variables. This nested hierarchy of variables was not proposed with the intent to suggest that all the variables are relevant for all the cases. Rather analysts might find the SES framework helpful as a diagnostic tool that enables them to define clearly variables of interest and organize them into connected groups [McGinnis and Ostrom 2014]. However, in this article, and according to the needed level of study and analysis, we will limit our forest system characterization to the first and second-tier variables (figure 3).

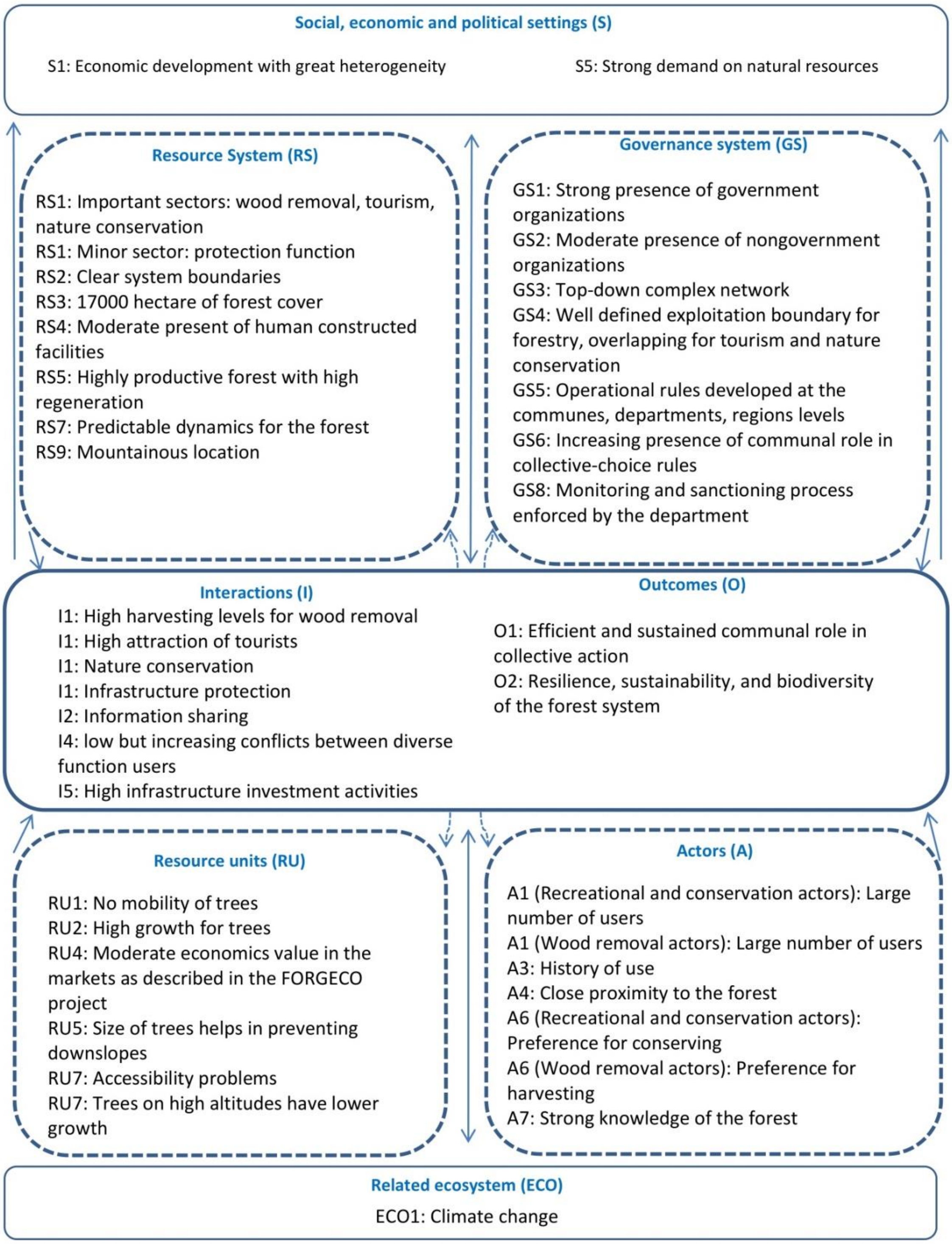


Figure 3. The modified SES framework for the Quatre-Montagne case study. Solid boxes denote first-tier categories; resource systems, resource units, governance systems, and actors are the highest-tier variables, in which they contain multiple variables at the lower tiers. Action situation is where all the actions take place as inputs and transform into outcomes. Dashed arrows denote feedback from the action situations to each of the top-tier categories. Exogenous influences from related ecological systems or social-economic-political settings can affect any component of the SES. We mention that we only outline variables we found relevant

to our case study through our identification method. For a more detailed view on the data and assessment method, see the appendix.

Resource system and resource units

The Quatre-Montagne SES (figure 3) can be characterized by the forest as a resource system. The forest cover is about 17000 ha and is labeled as public (owned by communes) (60%) and private (40%). The area contains a lot of human-constructed facilities related to tourism (accommodation, restaurants, sports and leisure, etc...), timber industry (side road wood deposition place, etc...), or both (i.e., roads) [Achard 2011]. Changing socioeconomic factors have led to a suite of land-use changes in the forested areas, and significant changes in the provision of some ecosystem functions [Parmentier 2013]. For example, using the forest as an obstacle against rockfall, conservation of the ecosystem (a forest reserve is the studied area), developing tourism (ex. ski resorts, green tourism), timber harvest, and many other functions.

Keeping in mind that the forest is generative in terms of wood production, tourism is also considered a major industry in the area; this is due to the mountainous terrain. Nevertheless, within the Vercors regional park, the forest participates in the image of “nature preservation” or “landscape esthetic” [Tenerelli et al. 2016] which, side by side with winter tourism, is the main engine for the local tourism. However, the area is widely exploited in terms of timber and in both public and private forests. Consequently, conflicts exist between different actors of the timber and tourism industry, the objective of the current forest management entails “produce more while protecting better” strategy [Achard 2011]. Within the forest, there are diverse species of trees such as Silver Fir, Norway Spruce, and European Beech, which makes its economic value high, but due to the topographic obstacle, timber industry faces particular difficulties linked to the mobilizing of the resource [Avocat et al. 2012]. Consequently, some parts of Quatre-Montagne forest are under-exploited [Puech 2009], which leads to the aging of these stands, and eventually, degradation of the wood production function.

Actors and governance system

Private forests

Since 1963, forest owners have been required by law to create a statutory document called “Plan Simple de Gestion” (PSG) to be validated by the regional centers of forest property (CRPFs). This document is described in the forestry code and integrated into the sustainable management policy of French forests [Tissot and Yann 2013]. PSGs must be in compliance with the regional woodland management schemes (SRGSs) set up by the CRPFs to define woodland management practices adapted to each region. Owners of small forests can either subscribe to a code of good forestry practices (CBPS) which makes forestry practices easier and permits them to receive subsidies from the state or file a management regulation.

Local and regional forests

The French forestry regime implemented by the ONF in public forests ensures the sustainable management of forest resources belonging to local and regional authorities. It is perfectly able to cope with the multiplicity of public owners and the need to combine the long-term rhythm with the forest short cycles of elected office. At the national level, annual timber harvesting is less than the annual forest growth, and thus, an increase of timber harvesting has been decided through the State-ONF-FNCOFOR (National Federation of Forest-Owning Communes) contract with the view of stabilizing the wood capital [Tissot and Yann 2013]. The income derived from timber harvesting is vital for rural communes. Activities around logging generate jobs that contribute to the maintenance of the population in rural areas. In addition, public forests provide open and accessible spaces for leisure activities. Fully aware of the multi-functionality of the forest, communes have combined the CFT with aims of proposing a conceptual framework to local stakeholders to integrate development of forests with participatory definition and precise objectives as well as local actions [Kouplevatskaya and Buttoud 2009].

Governance

The bulk of the funding of the governance functions comes from the subsidies that are offered by the European Union (EU) for supporting multifunctional and sustainable forest management [Sarvašová et al. 2014]. The state, as a central decision-making apparatus, has through a mutual adaptation of priorities and positions given the leading role in the CFT to the communes represented at the national level by the FNCOFOR. However, according to France's decentralized forestry regime, the governance functions are shared by three different organizations (Communes, Departments, and Region; see figure 2). First, municipalities are considered as owners of public forest and they act on the forest through the ONF to elaborate management plans and to exploit the communal areas following regional and national recommendations for biodiversity and environmental preservation. In addition to setting up the "rules-in-use" of public infrastructures, municipals invest (with subsidies from the EU) in infrastructures for the enhancement of user-forest interactions. Second, the department is responsible for sanctioning and monitoring, and establishing sensible areas to protect biodiversity, and additionally, departments receive subsidies by the EU to construct roads to enhance accessibility to the forest and facilitate timber mobilizing in the area. Third, the objectives of the regional organizations consist of mobilizing timber for exploitation and deploy snow canons as an artificial technique to assist winter tourism. On one hand, all forests belonging to municipals or public organizations are considered to be a public utility and therefore managed according to the French forestry regime, where forests are liable to strict management planning. This management has to integrate the multifunctionality of the forest and not just wood production. On the other hand, the PSG document is described in the forestry code and integrated into the sustainable management policy of French forests. The regional strategic documents of sustainable forest management are all approved by the state, for public forests as well as for private forests. The composition of regional commissions reflects the diversity of the actors involved in forestry at regional level [Tissot and Yann 2013].

Key elements and conclusions of the SES analysis

Tourism and nature conservation

Forests are a very important part of the landscape, especially in the Vercors area. Many outdoor recreational activities can be undertaken in a forested area. Though the mere existence of forests in the area may not be enough to promote tourism, but other activities, services, and infrastructures are also required. Moreover, nature conservation is an important function of the forest contributing to the increase of the forested area, enhancing the ecology of the forest and its sustainability. Although these two goals frequently reinforce each other, sometimes pursuing both simultaneously can result in conflicts [Lafond et al. 2017]. In some cases, recreational use can severely degrade an area that not only its environment is damaged, but also the quality of the recreational experience itself is diminished [Cole 1993]. The closure of the landscape can be detrimental to scenic beauty, and thus to recreational activities [Dunford et al. 2017]. The SES framework analysis indicates that in the sites where tourism has been promoted, for instance, through the establishment of protected areas, there are apparent economic benefits for the local population. However, tourist activity in natural areas needs to be managed carefully, as well as planned and organized in advance, in order to maximize the benefits for locals and enhance nature conservation at the same time.

Forestry

As shown before, the Quatre-Montagne forest varies greatly in terms of tree species, productivity, major roles, and ownership. Forest cover is increasing in the area [European Observatory of Mountain forests 2000]. Furthermore, adding on its contribution to tourism, the forest plays a significant role in the economy of the area through providing employment, maintenance, harvesting, and fuelwood. Moreover, wood production and fuelwood production is considered the most important aspect of the Quatre-Montagne forest. Nevertheless, in order to meet the demand on the forest, exploitation has to increase [Tissot and Yann 2003]. Some behavioral reluctances are added to technical and economic difficulties; the topography infers another obstacle, which has some effect on the price of the timber. The number of forest holders using skidders has decreased, whereas 62% of Rhone-Alps forest area is considered as “difficult to exploit” [Avocat et al. 2012].

Road infrastructures

The FFN (National Forestry Fund) had a strong impact on the environment and the economy in the area. It led to a quick increase in the forest area and allowed for the creation of infrastructure (i.e., roads and tracks) which made logging easier and more efficient [Tissot and Yann 2013]. Nevertheless, as a mountain forest, infrastructure provision (forest roads) in the Quatre-Montagne area is generally perceived as being scarcer and of poorer quality than in other parts of Europe due to its topology. For example, FORGECO [2014] shows, by the method of digital terrain models, that 36% of the forested area in the Quatre-Montagne is actually non-accessible, and thus, not efficiently exploited. Evidently, the area is lagging behind and faces difficulties related to lack of accessibility, which restricts both forest industries and recreation [Mountain areas in Europe – Final report 2004]. Reduced accessibility is consequently the most unanimously recognized drawback of the Quatre-Montagne forest compared to other forested areas across Europe.

Conclusions

The development of wood exploitation in the Quatre-Montagne area refers to the way resources may be appropriated in a highly heterogeneous area. The economic and logistic construction of the wood supply chain has to deal with a constraining geographic frame (including the difficulties to access the resource), the multifunctionality of the mountain forests (i.e., through maintaining the landscape beauty and biodiversity which is essential for tourism and nature conservation functions, respectively), and the fragility of the ecosystem [Mina et al. 2017]. Moreover, beyond the mobilization of technical disposals to improve the performance of the forest function (which enhances economic environmental efficiency along forestry and recreational activities), identifying and understanding the structure the forest SES and its dynamics are conditions for its sustainability and thus for the sustainability of the services it provides (e.g., forestry, tourism, etc.).

Moreover, the diverse processes launched by timber users on one hand, and by tourism and nature conservation users on the other hand, have made clear the need for a common language between the different functions committed. Such a common language will have to be built at different institutional levels, between actors having to confront their strategies at their temporal and spatial scales.

FOREST MULTIFUNCTIONALITY THROUGH THE ROBUSTNESS FRAMEWORK

Introduction

Muneepeerakul and Anderies [2017] suggests that the notion of social-ecological systems frequently used to frame common pool resource (CPR) problems does not adequately capture important aspects of hard human-made infrastructures that condition the interaction between social and ecological components in all SES's (i.e., spillovers, Anderies et al. [2016]). Nevertheless, the importance of applying the SES framework lays in the analytical description of the case study in hand that embraces institutional complexity by going through multiple tiers of variables. However, recent movements have distinguished between the applications of the SES and other frameworks. For example, McGinnis and Ostrom [2014] distinguish between the SES framework that captures the natural dynamics in SESs, and the social-ecological-technical system, where the constructed dynamic process of complex interaction is highlighted. In this vein, Muneepeerakul and Anderies [2017] seek to address problems associated with the fact that the importance of infrastructure is often invisible to users until it fails. The commonly used term "social-ecological systems" typically emphasizes the interaction between a set of infrastructure related to social and ecological processes [Ramaswami et al. 2012].

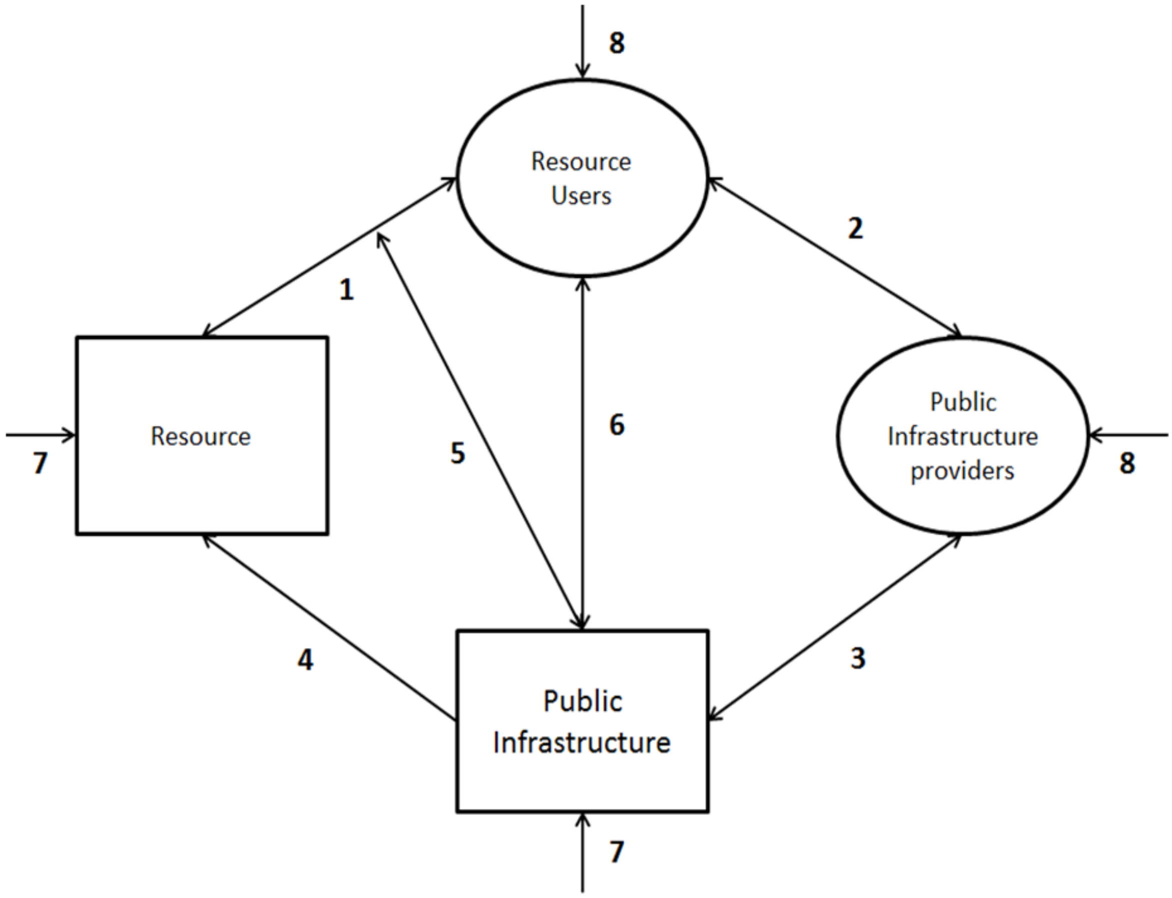


Figure 4. The conceptual model of the robustness framework as introduced by Anderies et al. [2004]. it specifies four generic components common to most social-ecological systems (resource, resource users, public infrastructure, and public infrastructure providers) and their interactions (Links 1 to 6). It also describes the presence of external disturbances (Links 7 and 8). Boxes refer to biophysical components of the system while circles refer to social components.

We use the robustness framework [Anderies et al. 2004] (figure 4) to analyze the dynamics of the forest SES. The framework delineates four components of the SES (resource, resource users, public infrastructures, and public infrastructure providers), their interactions, and how these components and interactions influence the capacity of an SES to cope with internal and external disturbances. As defined by Anderies et al. [2016], there are 5 main types of infrastructure considered by the framework: (1) hard infrastructure which is human-made structures such as roads; (2) soft infrastructure which are collections of human-made "instructions" for using other types of infrastructure such as institutional arrangements and decision making processes; (3) natural infrastructure which is hard infrastructure that is not human-made but is critical for society (the forest); (4) human infrastructure which refers to knowledge; and (5) social infrastructure which refers to the relationships we have with others. The framework explicitly recognizes the role of public infrastructures in influencing the system on the component level. Public infrastructure can be either "hard" or "soft" and is typically designed to achieve certain societal output [Muneepeerakul and Anderies 2017].

The robustness framework can be used to provide a systematic way of thinking that focuses on how these different infrastructures interact in terms of the functions they provide that avoids artificial and potentially misleading distinctions between various systems. Moreover, recognize and clarify the "configural" nature of the system, i.e., a minimal set of infrastructure classes is required before interesting higher-level organizational patterns emerge (i.e., well-being, communities, societies, etc.). When thinking in terms of robustness framework, the question is not "what is the right policy or set of institutions for a particular problem or context?" but, rather, "what infrastructure can we influence that might nudge the system to evolve toward a robust configuration that produces mass and information flows valued by the society?" [Anderies et al. 2016]. In what follows, we provide a general analysis, adopted from the SES framework analysis, of the case study through the robustness framework perspective. In particular, we use the robustness framework to provide an infrastructural point of view of some of the forest functions, and in the process, emphasize the importance of infrastructures in contributing to the operation and development of each of the functions mentioned (Table 1).

Timber and biomass for energy functions

The forestry sector is an important wood provider for basic human needs and an important employer and has the potential to create even more jobs in the future. Moreover, according to the Comité du massif des Alpes set up by the French national planning agency, sustainable planning of the forest harvesting will have become an important issue by the year 2020, and the energetic valorization will be a part of the alpine forest strategy [Avocat et al. 2012]. Several planning tools (e.g., Schéma stratégique forestier du massif des Alpes and the Inter-regional Convention for the Alpine Massif) clearly aimed at a rise of wood (e.g., fuelwood) utilization in the Vercors, if it meets mountain specificities and their vulnerabilities. Thus, the development of the forestry sector is obviously based on an increase in wood demand [AGRESTE 2014]. Table (1) shows the timber and biomass for the energy function of the forest through the point of view of the robustness framework. Forest owners use physical and social infrastructure to help in wood production from the forest, and in the process, the forest owners acquire characteristic information about the forest (Link 1). Resource users (RU) provide money to the public infrastructure providers (PIP) in the form of taxes, which allows for its operation, and in addition, resource users elect the public infrastructure providers and pay taxes (Link 2). PIPs produce public infrastructure (PI), both physical and social, such as roads and forestry organizations, and in return, information flows back (Link 3). PIP, through building PI, aims not just to offer a tool for enhancing wood extraction, but also to enforce rules through which it can prevent overexploitation and degradation of the forest. Information about forest owner's activity flows back to the PI (Link 5). Additionally, PI enables or restricts actions of RUs by providing knowledge that changes RUs perception. For example, the change to multifunctional forest management due to a better perception of knowledge (Link 6).

Tourism function

As shown before, tourism industry and the presence of large numbers of tourists has played an important role in mountain transformations in recent decades within many European countries, particularly in the Vercors, where tourism in some locations dates back to the mid-19th century. Table (1) shows the tourism function through the point of view of the robustness framework. Tourists take advantage of physical and social infrastructure to produce cultural services from the forest and conversely publicity and information about the resource flows back to the users (Link 1). Tourists and tourism companies contribute to governance (PIP) in the form of TVA taxes, permits, license fees, and elections (Link 2). The government uses the obtained tax money from tourists to construct PIs that are essential for the development of tourism in the forest (Link 3). Infrastructures contribute to the publicity of tourism in the forest as well as facilitate touristic activities (Link 5). In addition, infrastructures provide knowledge for the industry and enforce laws on tourists (Link 6). In return, infrastructures collect information on the tourists and their activities in the forest, in which it can help impose laws and adopt new management strategies for recreational activities.

Nature conservation function

The Vercors forest belongs to one of the most important ecosystems in Europe, and as such, it is subject to a nature conservation function [Sarvašová et al. 2014]. Despite the successful implementation of multifunctional forest management in the Vercors, conflicts between nature conservation and other sectoral policies regarding management of mountain forests were reported from some regions. Table (1) presents the nature conservation function through the perspective of the robustness framework. Conservationist and forest managers (e.g., ONF) help in conserving the forest through the utilization of infrastructures (associations, environmental organizations, and scientific studies), and information is gathered on the ecology of the forest (Link 1). Forest users participate in electing representatives in governance (Link 2). In return, governance produces infrastructures such as PNR, protected areas, and environmental laws that can help in the forest conservation process (Link 3). Furthermore, organizations enforce laws that benefit the preservation of nature and thus enhance the effort exerted by conservationists on the forest (Link 5). Additionally, organizations contribute to an increase in the nature conservation activities by providing knowledge to users and spreading out awareness (i.e., PNR) (Link 6).

Table 1. Forest functions from the point of view of the robustness framework and infrastructures. The table also shows the placement of the relevant SES variables associated with components of the framework. The "+" measurements signify the importance of the types of infrastructure to the functionality of their relevant infrastructure (see appendix for more information on the measurements)

		Functions			
Robustness framework	Forest (RS3)	Timber production/ biomass for energy production (RS1)	Tourism (RS1)	Protection (RS1)	Nature conservation (RS1)
	User activity	High (A1, A3, A4, I1)	High (A1, A3, A4, I1)	Low	High (A1, A3, A4)
	Users	Forest owners, and communes (A1)	Tourists, ski companies (A1)	Tourist, Foresters (A1)	Conservationist (A1)
	PIP	Municipals, departments, regions (GS1, GS3, GS5, GS6)			
	PI	Roads, sawmills, ONF, DDT, CCMV, etc. (GS1, GS2, RS4)	Roads, PNR, CCMV, restaurants, ski centers, etc. (GS1, GS2, RS4)	none	PNR, DDT, CCMV, Protected areas, etc. (RS4)
	Link 1 (U↔Forest)	Timber exploitation (A6, RS2, RS5, RU2, RU4, I1, O2)	Cultural services (A6, RS2, RS9, I1, O2)	Infrastructure protection (I1, O2)	Conservation of natural infrastructure (A6, I1, O2)
	Link 2 (U↔PIP)	Elections and taxes (GS6)	Elections, TVA, and license fees (GS6)	none	Elections (GS6)
	Link 3 (PIP↔PI)	Provisioning of forest roads and forestry institutions (RS4, I5)	Provisioning of accessibility, rangers, accommodations, etc. (RS4, I5)	Provisioning of natural infrastructure through tree planting (RS4, I5)	Provisioning of forest regulations and nature conservation institutions (RS4, I5)
	Link 4 (PI↔Forest)	none	none	none	none
	Link 5 (PI↔Link 1)	Harvesting and regulations for preventing damages for the forest (GS5, GS8, RU7, I1, S5)	Regulations for limiting the effect on the forest ecosystem (GS4, GS5, GS8, RU7, I1, S5)	none	Enhancement or restriction of the effort for conservation (GS4, GS5, GS8, RU7, S5)
	Link 6 (PI↔U)	Guarantying sustainable forest management (RS7, GS4, RU4, RU7, I2, I4, O1)	Constraining the access to the forest to avoid conflicts and limits negative environment impacts (RU7, A7, I2, I4, O1)	none	Increasing nature conservation activities through regulating forest management practices and monitoring (RU7, A7, I2, I4, O1)
	Link 7 (exogenous variables affecting natural and human-made infrastructure)	Climate change (affects tree growth, survival, and regeneration, ECO1)	Climate change (affects ski tourism and related activities, ECO1)	Climate change (more fires or insects inducing secondary natural hazards, ECO1)	Climate change (affects the biodiversity and forest ecosystems, ECO1)
	Link 8 (exogenous variables affecting social infrastructure)	Market variability (S1, S5)	Strong demand (S1, S5)	none	Social incentive (S5)
	Soft-human made	+ (DDT, ONF, CCMV, etc.)	++ (PNR, CCMV, etc.)	+ (ONF)	+++ (PNR, DDT, CCMV, etc.)
	Hard-human made	+++ (Roads, sawmills, etc.)	++ (Restaurants, ski centers, roads, etc.)	+ (None)	+ (None)

Infrastructures	human	++ (Forest owners)	+++ (Tourists and business men)	+ (Tourists and foresters)	+ (Conservationist, tourists, foresters)
	Social	+ (web of relations between forest owners)	+++ (Publicity and web relations)	+ (information sharing with the ONF)	++ (Awareness and web relations)
	Natural (forest)	+++ (Trees)	+++ (Natural environment)	+++ (Trees)	+++ (Natural environment)

Protective function

Mountain forests in the Vercors have an important protective function against natural hazards such as rockfall, snow avalanches, shallow landslides [Aggestam and Wolfslehner 2013]. The primary function for the protection forest is to protect people and assets from the impacts of natural hazards. The key products of the forest are the standing trees that act as obstacles for the triggers of mass movements and downslope propagation hazards. Table (1) expresses the protective function of the forest from the robustness framework perspective. Users (i.e., forest owners, public, and private organizations, etc.) use strategies to concentrate the forest with the purpose of protecting infrastructures (Link 1), in return, users participate in the election of the government (Link 2) which, in terms, provide infrastructures that are essential for the operation of this function (Link 3). All of these interactions occur while information eventually flows back to the resource.

Exogenous variables

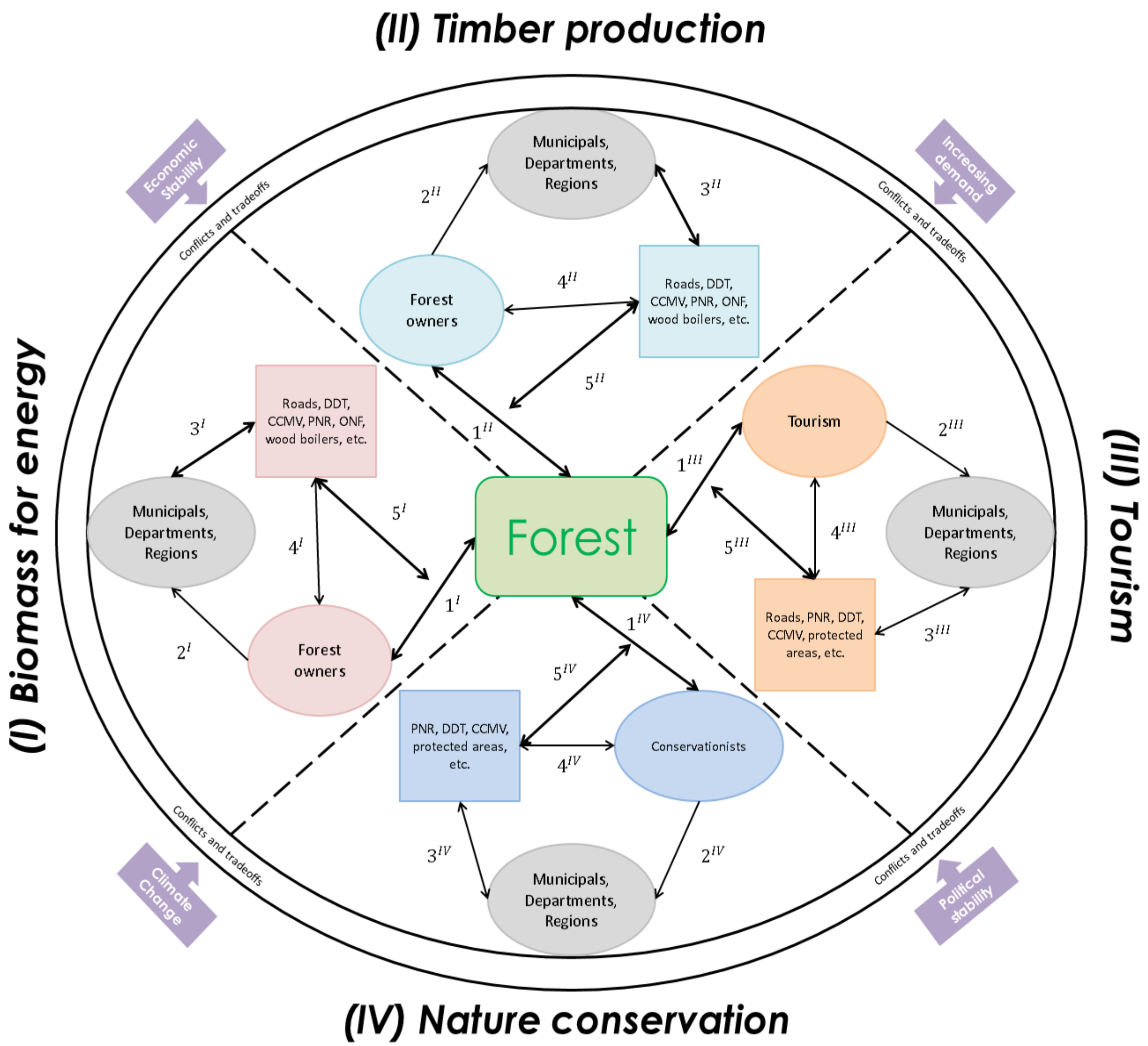
Although the forest is a system that is governed by social and ecological subsystems, it is also affected by exogenous variables that are influencing the forest at a global scale. Economic instability impacts timber and fuelwood markets and introduces high variability and uncertainty in the stock market. Nevertheless, global climate change also has an effect on the ecology of the forest (at the regeneration, growth, and survival levels) and, consequently, on the functions of the forest. Additionally, Snow scarcity has significantly impacted snow tourism. In the Quatre-Montagne, negative impacts of climate change were evident for the provision of ecosystem functions. Synergies and trade-offs between the majority of forest functions were found to be sensitive to the choice of management and climate change [Mina et al. 2017].

ANALYSIS AND DISCUSSION

We have explicitly applied the two frameworks (SES and robustness frameworks) in a complementary manner as a tool to explain institutional analysis behind multifunctional forest management, in which we conceptualize the link between interactions and outcomes within the SES framework. In particular, after acknowledging its powerful capacity for analysis and deduction, we use the SES framework to introduce a general support for the institutional analysis. Moreover, we recognize the importance of the infrastructure concept and the role of spillovers [Anderies et al. 2016] in affecting the outcomes of the forest. For example, considering a lack of roads can have several effects, one of which it will limit affordance for people to be able to exploit timber in the forest, this may lead to a reduction of the negative effect of tree cutting on some specific forest-dwelling species [Paillet et al. 2010]. Ideally, we use the robustness framework to conceptually represent forest multifunctionality as it adequately captures such infrastructure concepts. From this, one can conclude that there are four functions that are widely practiced in the Quatre-Montagne forest (timber production, fuelwood production, tourism, and nature conservation; protection function being not so important in this area, see table 1). These functions, however, interact in a complex manner (highlighted by the many trade-offs emerged between functions; i.e., impact of tree removal on the biodiversity and scenic beauty of the forest that impacts tourism and nature conservation) impacting not only the dynamics of the forest as a natural infrastructure, but also the production capabilities of one another. Furthermore, these interactions between functions, as characterized by our analysis, are occurring on the infrastructure level. Such perspective has identified a link between the concept of multifunctional forest management and multifunctionality of different types of infrastructures (as defined by Anderies et al. [2016]). Consequently, when viewing each function from the lens of the robustness framework along with outlining related infrastructures, keeping in mind that there are common infrastructures for different functions, the link can be visible. Thanks to this, we conceptually describe multifunctional forest management by associating types of infrastructures to relevant SES framework variables pertinent with the case study. Such characterization has not only allowed for the identification and organization of general components that are functioning in the forest but also difficult-to-observe spillovers between types of infrastructures of different functions. Through connecting forest multi-functionality to the multi-functionality of infrastructures, we illustrate how qualitative analysis can be used to conceptually describe and organize components to help in designing governance and management strategies (see section 5.3).

5.1 Characterizing the dynamics of the forest

Thanks to our complimentary framework application, we have qualitatively characterized the link between multifunctional forest use and the multi-functionality of infrastructures in an SES context. Such characterization has allowed us to conceptually organize the relationship between interactions within SES framework and the actual outcomes. The knowledge of how the different infrastructures of each function interact to affect one another and to produce resources from the forest is essential from a management perspective (what infrastructures interact and how). Our analysis has provided us with a characterization of a multifunctional forest management view of the system with visible connections between the different function-related infrastructures. Figure (5) represents a modified conceptual map of the robustness framework that takes into account the four important functions in the Quatre-Montagne forest.



Interaction	Description
$1^{I}, 1^{II}$	Wood exploitation
1^{III}	Cultural services
1^{IV}	Conservation of the forest
$2^{I}, 2^{II}, 2^{III}, 2^{IV}$	Taxes and election participations
$3^{I}, 3^{II}, 3^{III}, 3^{IV}$	Provisioning of infrastructures and institutions
$4^{I}, 4^{II}$	Limits tree removal, devise exploitation plans, enforce laws, etc.
4^{III}	Enforces laws, plan accessibility, etc.
4^{IV}	Provide nature conservation activities, and plans protected areas
$5^{I}, 5^{II}$	Exploitation regulations
5^{III}	Regulations and services
5^{IV}	Enhancement and restriction of effort

Figure 5. Forest functions from the point of view of the robustness framework's conceptual map. The thicker the arrow, the important the interaction.

5.2 Governance characterization

The application of the robustness framework has provided us with a qualitative linking between forest functions and infrastructures. Governance, being an infrastructure provider, is a critical point in determining how the exploitation system evolves in the forest. Their role in promoting and maintaining industrial activity through developing infrastructures is essential for the development of functions in order to comply with market demand. Multi-functional forest management can be difficult to achieve without a proper infrastructure framework and mechanism. Decisions about infrastructure alignment, building, maintenance, or decommissioning are complex because of the many tradeoffs involved [Lugo and Gucinski 2000]. One example is the conflict emergence between forestry and nature conservation functions as a result of increasing road infrastructures that allow cuttings in more forested area which can be damaging for nature [Caliskan 2013]. This calls out for systematic tools that are able to explain the effect of decisions of investments in infrastructures. Figure (5) shows how governance is represented by their ability to produce infrastructures that give affordances for users to exploit the forest.

5.3 A function or an infrastructure?

Well planned design and robust approaches to conceptualization of forest socio-biophysical interactions is a critical component of its management [Prato and Paveglio 2014]. The importance increases as forest provision demand becomes closely tied with societal incentives. As outlined earlier, managing forests for different functions may be enhanced by carefully designing investments in the provisions of associated infrastructures for each function (i.e., social, human, hard human-made, etc.). For example, prior to introducing new public hard human-made infrastructures, the government has to be able to maintain them to avoid a cascading failure; this is done through additional investment in infrastructures that can give affordance for maintenance (human and social infrastructures). Adding on this, recent work [Rose 1986, Frischmann 2005, Anderies et al. 2016] analyzes the ways in which the special nature of infrastructure affects both how it is provided and its impact on economic activities. Essential to this argument is thinking carefully about the many ways infrastructures generate difficult-to-observe effects that generate values to society. Thinking in terms of positive and negative effects of infrastructure interactions have been used by Anderies et al. [2016] in the coupled infrastructure systems representation. In fact, the authors argued that not considering these effects can distort institutional analysis by placing too much emphasis on the problem of providing infrastructure and allowances for suppliers to capture the benefits of infrastructures while neglecting the importance of demand for the many values infrastructures may provide. This paper has identified a link between how multi-functional forest management evolves and abundance of relevant infrastructures. The present work highlighted the control of the governance on the development of forest functions through provisioning of infrastructures. Investing in function-related infrastructures may contribute to the progress of this function. In other words, in the Quatre-Montagne forest, one needs to reinforce both hard and soft infrastructures to enhance multifunctionality. For example, the development of timber function depends on the investments in "accessibility infrastructures" such as roads.

Therefore, a suitable design of infrastructures can contribute to a better application of the multifunctional forest management by putting an emphasis on forest function-related infrastructures more than others.

		Timber production/ biomass for energy production	Tourism	Nature conservation
Infrastructures	Soft-human made	+ (DDT, ONF, CCMV, etc.)	++ (PNR, CCMV, etc.)	+++ (PNR, DDT, CCMV, etc.)
	Hard-human made	+++ (Roads, sawmills, etc.)	++ (Restaurants, ski centers, roads, etc.)	+ (None)
	human	++ (Forest owners)	+++ (Tourists and business men)	+ (Conservationist, tourists, foresters)
	Social	+ (web of relations between forest owners)	+++ (Publicity and web relations)	++ (Awareness and web relations)

Figure 6. Effect of investments in hard-human made infrastructures for forestry functions. Green signifies investment, blue first-tier effect, orange second-tier effect, and purple third-tier effect. The signs +, ++, and +++, refer to the importance of the infrastructure to the relevant forest functions (for more information see table 1 and the appendix)

Using a qualitative conceptual map, our complementary framework application can identify how the nature of one function-specific infrastructure affects the different natures of other function-specific infrastructures. For example, concluding from table (1) and particular to the Quatre-Montagne forest, figure (6) shows, on one hand, that investing in hard-human made infrastructures for forestry functions (e.g., roads) offers more accessibility for tourists, which in turn require more investments in other infrastructures for the tourism function such as social infrastructures (e.g., publicity) in order to comply with the market demand. On the other hand, such investment may increase potential conflicts between multiple forest functions, such as wood production and nature conservation and recreation, which then require more social capital between stakeholders. This generic view of forest multifunctionality has presented a qualitative and systematic investment decision tool that synthesizes the different effects one investment can apply to other infrastructures related to the same forest function as well as other functions.

CONCLUSIONS

We have developed a method that examines the SES concept with a focus on multifunctional forest management. Through our analysis, we have highlighted the spillovers that can occur between functions through the concept of infrastructures (see figure 6). Using an example, we have attempted to demonstrate that the resulting complementary framework application can be used to examine problems associated with shared and multifunctional infrastructures for multiple forest functions. The picture that emerges from our methodological applications shows that careful infrastructure investment strategies are needed in order to closely enable multifunctional forest management. Moreover, it is essential to grasp the relationship among the contributing infrastructures and their inner relations with a focus on the notion of spillovers. The complexity that can arise from the interactions of different forest functions admitting different (and maybe conflicting) objectives would argue against highly simplified approaches of multifunctional forest application. We conclude by discussing the following points: (1) the paper contribution to forest governance (2) it's methodological contributions (3) its use for potential future works.

The economic development of forest functions has to deal with some constraints of managing multi-functionality: the fragility of the ecosystem and the geographic constraints that limit the accessibility to the forest. The main aspect influencing the outcomes of forest functions is the availability of infrastructures highlighting their importance in enabling multifunctional forest management. In this vein, it is necessary that the design, establishment, and management of infrastructures be carried out by taking into account the values and functions provided by the forest. This paper has provided an insight for analyzing and designing infrastructural systems that implement multifunctional forest management. We have also highlighted the concept of spillovers and their importance in forest governance, and especially, in the context of multi-functionality. However, because of the nature of qualitative assessment adopted in this work, much is needed in formalizing spillovers in a comprehensive governance theory for multifunctional forests. In particular, there is a need for more comparative in-depth case studies using the same infrastructure-connected variables measured with the same protocol.

Our methodology has opened a prospective for a direct link between the SES and robustness frameworks. This link is illustrated in the ability of the robustness framework to conceptually describe the complex relationship between Interaction (I) and Outcomes (O) found in the SES framework in the case of SESs that depend heavily on infrastructures. This work can thus be useful for deriving conclusions for governance of SESs. We have applied the methodological nature of our work to the Quatre-Montagne forest in order to facilitate the comprehension of our approach. Although we have chosen a forest case study to highlight the multi-functionality concept, we mention that this concept has recently gained fame within managed ecosystems (rivers, streams, and lakes [Podolak 2012, Munch et al. 2016, Habersack et al. 2018], agricultural systems [Ricart et al. 2019], fisheries [Mulazzani et al. 2019]). We hope that this work can be a first step toward the inauguration of multi-functionality concept with existing SES frameworks.

Our analysis can open the door for developing operational tools that can help to better devise multifunctional management strategies taking into account the social and ecological aspects of an SES. One example of such use of the robustness framework can be found in the paper written by Muneepeerakul and Anderies [2017], in which the authors operationalize the framework's conceptual map to build up a mathematical model that explores the circumstances of the emergence of stable governance. There is still a lot to gain from merging mathematical tools (dynamical system theory, viability theory, etc.) in the framework's conceptual map that can contribute to more generic models for SESs management.

LITERATURE CITED

At the end of the manuscript

Appendix – Data extraction and measurement

The data used to build up the analysis has been taken either from French national project [FORGECO 2014], European project [ARANGE 2015] or literature about the case study from a search in the Scopus database; for more information about the source of data, see table (S1). FORGECO project aimed to develop a territorial forestry approach based on the principles of integrated management of ecosystems that can accompany and organize the increase in harvesting of the resource and better preservation of biodiversity and soil quality. There was one mountain forest case study approached, Quatre-Montagne forests. The survey focuses on the participatory and adaptive approach to forest management expertise and its ecological and socio-economic vulnerabilities and the development and evaluation of scenarios for intensifying forest management. In order to allow spatial and temporal integration of information and to support decision-making process, the project is based on the construction of decision-making tools, each of which possesses a generic character: (i) model resource dynamics and mobilization (ii) habitat quality model (iii) scenario analysis using the production boundary method, (iv) resilience and scenario viability analysis, (v) participative approach structured by the method of the territory game [Lardon et al. 2016]. Moreover, ARANGE project [Bugmann et al. 2017] objective was to analyze the multifunctional forest management for several case studies in Europe (seven mountain forests across Europe; Montes de Valsain (Spain), Quatre-Montagne (France), Montafon (Austria), Sneznik (Slovenia), Vilhelmina (Sweden), Kozie Chrbty (Slovakia), Shiroka Laka (Bulgaria)). This scientific synthesis integrated the findings from generic and case study specific analysis to develop a web-based decision support toolbox for multifunctional mountain forest management to support interested stakeholders beyond the time span of the project. The main bases for the project are (i) the use of regional case studies, (ii) stakeholder's involvement in the analysis, (iii) the use of models and tools to predict forest conditions and assess ecosystem services, and (iv) establishing new plans and decisions support tools.

The processes of diagnosing important SES framework variables were conducted by the following steps:

1- Identify the main component of the Quatre-Montagne forest SES (governance system, resource units, resource system, and users).
2- Describe the natural variables that affect each of the forest functions and eventually the governance revolving around them.
3- Identify the general action situation in which the functions interact.
4- Explore the links and relations between governance and forest functions' performance.

These four steps require figuring out which variables from the SES framework are essential and descriptive. Using the data collected, we use two types of assessment methods for variables' importance:

1- The assessment of the variables from the literature and reports (found in table S1) of the projects depending on the language of the text in which they are described in (see assessment in table S1).
2- Authors' knowledge and expertise on the case study, which determines the variables and infrastructures that are most relevant to the function

As mentioned in the main text, the qualitative comparisons that describe the variables in the SES framework (moderate, strong, high, low) are relative to other mountain forests studied by the ARANGE project. For this, we mention that these case studies are already compared with each other within the text's language of analysis and studies of the ARANGE project.

Moreover, building on the description offered by the SES framework analysis, we constructed the robustness framework analysis by describing its conceptual map for every forest function, essentially through identifying the main components of the robustness framework and characterizing their interactions. Furthermore, the importance of types of infrastructures for each forest function (+, ++, and +++) is measured by the criteria described above as well. We give the following examples to facilitate assessment comprehension:

- We conclude through the SES framework's analysis that accessibility is a main issue for the wood production function (see variable I5-infrastructure investment activities and RS4-human-constructed facilities), which implicates that hard human-made infrastructures, which are mainly composed of roads, are of great importance for the function. This implies the +++ measure.

- Variables A6 (norms/social capital), A7 (Knowledge of the SES), O1 (social performance measures) suggest that nature conservation requires a lot of social capital to function and develop implying the importance of soft-human made infrastructures, which are presented by a set of rules. This implies the +++ measure.

- Variable I2 (Information sharing) advocates that the web of relations between forest function actors is important to increase the performance of the nature conservation function, which implies the importance of social infrastructures. Although the hard-human made infrastructure is important, one can qualitatively evaluate through author's expertise and literature language that the infrastructure is not as important as the norms and rules (soft-human made infrastructure) for the performance of nature conservation. This implies the ++ measure.

Table S1. A table presenting the relevant SES framework variables, their assessment method, and the data used for the assessment method (source of data and type of study)

Data used for assessment / Variable	Source (type of study)	Assessment
RS1 – sectors	Mountain areas in Europe 2004 (Reports), FORGECO 2014 (French national project), ARANGE 2015 (European project)	These projects highlighted the different functions and their importance (tourism, wood production, and forest conservation), and as such, they studied the multifunctional forest management shedding light on the different conflicts that arise between them.
RS2 - clarity of system boundaries	Tissot and Yann 2013 (Report)	This reference analyzed the forest policy in France, explaining the property rights of owners including their property boundaries.
RS3 - the size of resource system	FORGECO 2014 (French national project), ARANGE 2015 (European project), Tenerelli et al. 2016 (Article)	The projects clearly defined the size of the forest through spatial measurements and fieldwork.
RS4 - human-constructed facilities	Achard 2011 (Report), FORGECO 2014 (French national project)	The references clearly stated the different human-built facilities in the forest (saw mills, roads, resorts, hotels, etc.)
RS5 - productivity of the system	FORGECO 2014 (French national project)	The project presented the different tree species found in the forest (e.g., Norway Spruce, silver fir, European beech) and discussed their abundance in the public and private forests
RS7 - predictability of the system dynamics	FORGECO 2014 (French national project), ARANGE 2015 (European project), Mathias et al. 2015 (Article), Lardon et al. 2016 (Book chapter)	Mathias et al. [2015] builds a mathematical model based on empirical biophysical data for the forest growth (data includes: tree regeneration, competition between small and big trees, mortalities, light interception, tree diameters, deadwood, and biodiversity, etc.). The article also tests different wood removal scenarios and predicts their impact on the forest. Moreover, FORGECO [2014] and ARANGE [2015] also analyze different multifunctional forest management scenarios predicting their impact on the forest as well as on the performance of other functions through diverse methods [e.g., method of territory game]
RS9 – location	Avocat et al. 2012 (Article), FORGECO 2014 (French national project), ARANGE 2015 (European project), Mathias et al. 2015 (Article), Lardon et al. 2016 (Book chapter), etc.	The Quatre-Montagne forest is located in the Grenoble agglomeration, at borders between northern and southern French Alps with a mountainous location

GS1 - government organizations	Kouplevatskaya-Buttoud 2009 (Article), Tissot and Yann 2013 (Report), Sarvasova et al. 2014 (Article), ARANGE 2015 (European project)	The references suggest a high presence of government organizations. All exploitation activities are referred to legal licenses and documents issued by government organizations. For example, the ONF (National Forestry Office) is one of the important government organizations with authority overlapping on regional, departmental, and communal levels.
GS2 - nongovernment organization	Tissot and Yann 2013 (Report), FORGECO 2014 (French national project), Sarvasova et al. 2014 (Article) ARANGE 2015 (European project)	The sources clearly outline the different nongovernmental organizations that interplay in the Quatre-Montagne, which ranges from organizations with exploitation and recreational objectives to organizations with nature conservation objectives. In addition, Sarvasova et al. [2014] assesses the contribution of such NGOs to the application of multifunctional forest management
GS3 - network structure	Tissot and Yann 2013 (Report), FORGECO 2014 (French national project), ARANGE 2015 (European project), Kouplevatskaya-Buttoud 2009 (Article)	The network structure is described as a top-down complex network with different governmental and nongovernmental organizations interacting on three different levels. Figure 2 in the main text explains the different levels of government organizations and the documents that are issued at each level.
GS4 - property rights systems	Tissot and Yann 2013 (Report)	Forest property rights are well known through a legal system determined by the French government. Nonetheless, Despite the efforts of property consolidation via exchange fairs or via the law, changes are slow. Forest is a property that is seldom exchanged.
GS5 – operational rules	Achard 2011 (Report), Tissot and Yann 2013 (Report), ARANGE 2015 (European project), FORGECO 2014 (French national project)	Operational rules are clearly defined through a legal system that gives licenses based on exploitation constraints
GS6 - collective choice rules	Tissot and Yann 2013 (Report), ARANGE 2015 (European project), Kouplevatskaya-Buttoud 2009 (Article)	Defined by the French decentralization system, local communities admit an increasing role in defining the rules for exploitation in the Quatre-Montagne, mainly though the CCMV (community of communes of the Vercors massif).
GS8 - monitoring and sanctioning rules	Tissot and Yann 2013 (Report), ARANGE 2015 (European project)	The monitoring of French forest policy is a very important task. Various instruments are designed to evaluate and monitor national and regional processes, and programs established by the government.
RU1 - resource unit mobility	Avocat et al. 2012 (Article), FORGECO 2014 (French national project), ARANGE 2015 (European project), Mathias et al. 2015 (Article), Lardon et al. 2016 (Book chapter), etc.	As trees are the main producer of wood and reinforce of recreation and conserver of nature in the forest, the resource unit (trees) are non-mobile. However, the growth and height of trees varies depending on the different elevations in the forest
RU2 - growth and replacement rate	FORGECO 2014 (French national project), ARANGE 2015 (European project), Mathias et al. 2015	Studies and dynamical models presented by both projects that analyze the replacement rates of trees, and analyze the different growth of trees depending on the elevation. These references refer to high growth of forest with respect to other forests in Europe

RU4 - economic value	Achard 2011 (Report), FORGECO 2014 (French national project), ARANGE 2015 (European project)	Studies the economic values of wood, deadwood, and fuelwood in the forest that are considered with a high value in the French market
RU7 - spatial and temporal distribution	FORGECO 2014 (French national project), ARANGE 2015 (European project)	In the projects, specific importance is given to the spatial distribution of trees with focused study on the effect of tree elevation on the growth of trees
A1 - number of relevant actors	Mountain areas in Europe 2004 (Reports), Tissot and Yann 2013 (Report), FORGECO 2014 (French national project), ARANGE 2015 (European project)	The references discuss the importance of forest with implications to the high touristic attractions in the area, which allows for the development of the industry. Moreover, the forest has a lot wood production actors in relative to its size
A4 – location	FORGECO 2014 (French national project), ARANGE 2015 (European project)	The close proximity of the forest to the agglomeration of Grenoble (a main city in France), has allowed for the development of tourism as an important economic driver
A6 - norms/ social capital	Mountain areas in Europe 2004 (Reports), FORGECO 2014 (French national project), ARANGE 2015 (European project)	Conflicts arise in the forest with different objectives. The references reported two preferences of the different actors: Tourism and nature conservation (with a preference of conservation), wood removal (with a preference of harvest)
A7 - knowledge of SES/ mental models	FORGECO 2014 (French national project), ARANGE 2015 (European project)	The projects did many studies and conceptual approaches to anticipate and gather information about the Quatre-Montagne forest SES
I1 - harvesting levels	Achard 2011 (Report), FORGECO 2014 (French national project), ARANGE 2015 (European project),	On one hand, harvesting levels for wood production are reported to be high with respect to other European mountain forest case studies approached with the project. On the other, the Quatre-Montagne forest is considered one of the most visited destinations for winter tourism. Moreover, the forest belongs to one of the most preserved ecosystems in Europe. Finally, infrastructure protection strategies are being used in the area
I2 - information sharing	FORGECO 2014 (French national project), ARANGE 2015 (European project)	Information sharing is an important aspect in the Quatre-Montagne and usually happen inside meetings and local chamber, one of which is the community of communes of Vercors massif (CCMV)
I4 – conflicts	Gonzales-Redin et al. 2015 (Article), FORGECO 2014 (French national project), ARANGE 2015 (European project), Lafond et al. 2017 (Article)	Conflicts are highly reported especially between the main forest functions: tourism, wood production, and nature conservation
I5 - infrastructure investment activities	Achard 2011 (Report), FORGECO 2014 (French national project), ARANGE 2015 (European project)	Infrastructure provision is a main issue in the Quatre-Montagne forest. On one hand, roads exhibit many negative impacts on scenic beauty and the ecosystem (i.e., implication with an impact on nature conservation function). On the other hand, and in the presence of accessibility problems, roads are essential for the development of forest functions, especially wood production function. European union offer a lot of subsidies directed towards development of infrastructure (which are mainly roads)

O1 - social performance measures	Kouplevatskaya-Buttoud 2009 (Article)	Social performance is demonstrated in the sustained and increasing role of communal role in the collective action within the forest
O2 - ecological performance measures	Onida 2009, Avocat et al. 2012, FORGECO 2014 (French national project), ARANGE 2015 (European project)	Legal application and management strategies have allowed for the sustainability of the forest and its resilience. Although climate change has made a huge impact on tourism performance due to the scarcity of snow (winter tourism), the government and management entities have limited this impact through the deployment of snow canons in the mountain ranges
ECO1 - climate change	European Observatory of Mountain forests 2009 (Reports), Bugmann et al. 2017 (Article),	Climate change has reported to have impacts on the forest system, with a great implication to the snow melting in the mountains
S1 - economic development	FORGECO 2014 (French national project), Sarvasova et al. 2014 (Article), ARANGE 2015 (European project), Bugmann et al. 2017 (Article)	These sources exhibited strong language in explaining the economic development in the Quatre-Montagne forest. Because the main study of these sources is multifunctional forest management, the economic development in the forest includes different functions with different background (social and ecological); this exhibit great heterogeneity in the overall economic development.
S5 – market	Tissot and Yann 2013 (Report), AGRESTE 2014, FORGECO 2014 (French national project), ARANGE 2015 (European project)	These studies refer to the strong demand on the forest. This demand is exemplified in social and ecological functions (tourism, wood production, and nature conservation). In particular, the references clearly presented the importance of the different functions with a focus on their development due to the strong demand they face. The Quatre-Montagne forest belongs to one of the most exploited ecosystems in Europe (critical source of wood and a very important touristic destination).

Chapter 3

An analysis-characterized mathematical model

3.1 A mathematical presentation of the forest complex system

Chapter 2 has lighted the way toward developing operational tools to explore decisions that mediate the management within multi-functional forests that depend heavily on infrastructures. Therefore, to fully integrate the role of shared infrastructures and their governance into ecosystem science, we propose a generic modeling approach based on the conceptual representation of multi-functional forests found in **Chapter 2**.

The article starts with building a mathematical model that is based on the conceptual representation of the multi-functional forest management developed in **Chapter 2**. The model takes into account the effect of infrastructures on the performance of three forest functions (wood removal, tourism, and biodiversity). In particular, the model adopts the concept of "infrastructure enhancement" endorsing their non-linear nature in their functionality and consequently models the process behind which infrastructures are provided. The model is simulated according to extreme cases of functions exploitation exploring the effect of different infrastructure provision strategies on their functionality. To assess the performance of multi-functional forest management with infrastructure provision strategies, we introduce a multi-functionality index that quantifies its execution. Using this, we explore conditions and potential for the fosterment of multi-functionality management with different weighted objectives in extreme exploitation cases.

3.2 Presentation and contribution of the article

The article has been submitted to *Earth's Future* journal. The main contributions are as follows:

- Development of a mathematical model based on conceptual SES-based analysis that explores multi-functional forest management;
- Presentation of conditions for the fosterment of multi-functional forest management;
- Exploration of different hard infrastructure provision strategies on the performance of multi-functional management, presenting trade-offs and non-symmetric effects that occur between functions.

3.3 Conclusions

Although the assumptions adopted in this paper on the nature of infrastructures are fairly basic, the infrastructure enhancement functions define a clear relationship between the ecosystem services and the biophysical environment of the forest. Moreover, such functions capture important aspects of infrastructures regarding the decision of exploitation (either functions use infrastructures for their benefit or don't). The built model focuses on analyzing the forest multi-functional management through the provision of physical human-made infrastructure, which highlights the role of governance.

This work can open a perspective to the development of much-needed, systematic mathematical analysis of coupled infrastructure systems [Anderies 2016], especially those focusing on multi-functionality concepts. There is still value in improving the model with a better indicator of biodiversity that can potentially better highlight ecological trade-offs in the forest. Moreover, much work is also needed with the introduction of the concept of adaptive management of infrastructures to maintain an SOS for multi-functional management. From a general standpoint, viability theory can be useful such a concept for governing functions as individuals and common safe operating spaces for the forest multi-functionality. This approach can bring new insights to the management and development of social-ecological systems encompassing a concept of multi-functionality.

3.4 Text of the article

An infrastructure perspective for enhancing multi-functionality of forests: A conceptual modeling approach

M. HOUBALLAH[1], JD MATHIAS[1], T. CORDONNIER[2]

[1] Université Clermont Auvergne, Irstea, UR LISC, Centre de Clermont-Ferrand, 9 avenue Blaise Pascal CS 20085, F-63178 Aubière, France

[2] Université Grenoble alpes, IRSTEA, UR LESSEM, 38000 Grenoble, France.

Corresponding author: Mojtaba Houballah (mojtaba.houballah@gmail.com)

Key points:

- A conceptual framework for a forest that is mathematically operationalized as a dynamical system.
- Study of interactions between forest functions in a multifunctional management context
- Analyzing multifunctional forest management through the multi-functionality of road infrastructure networks

ABSTRACT

Many forest resource systems depend heavily on shared and coupled infrastructures in applying their management strategies. Addressing a question of sustainability for relevant contemporary social-ecological systems can be tackled by understanding how these shared infrastructures mediate the interaction between human and ecological environment. Shared infrastructures, which are mainly composed of roads (accessibility utilities), highlight the relation between the performance of ecosystem services and the multifunctional use of the forest. However, dilemmas associated with road provision pose some problems when it is applied in a forest multifunctional management context because roads potentially diminish or enhance forest functions in a complex way. In this context, maintaining, fostering, and improving multifunctional management where the development of an ecosystem function can affect the performance of others is challenging. We propose to develop a mathematical model based on a recent study that links multifunctional forest management to the multi-functionality of forest roads by using the social-ecological system and robustness frameworks. With this model, we analyze the evolution of the forest system and three key forest functions (wood production, tourism, and nature conservation) when impacted by decisions of road provision. We then examine how governance provision strategies can affect the performance of functions and how these strategies can potentially foster forest multi-functionality. This approach allows us to derive conditions of sustainability in which decisions of shared infrastructure provisions can play an important role in the functionalities and performance of the forest.

Plain Language Summary

To understand how the forest evolves in a multifunctional management context where shared infrastructures mediates the interaction of forest functions (wood production, tourism, and nature conservation), we develop a theoretical – but informed by a real case study – mathematical model based on the famously used socio-ecological robustness framework that focuses on the infrastructure role in the performance of the forest's functional systems. We define a concept of multi-functionality index as a way to quantify the performance of forest multifunctional management. This model integrates governance and highlights it by its ability to provide infrastructures. Analysis of the model results in an examination of the emergence of multifunctional forest management with a significant correlation with forest governance, and a study that deals with the sustainability of such ecosystems that are expressed as a clear relationship between biophysical and social structures.

2. INTRODUCTION

Services provided by forests are crucial to our survival and humans probably could not live without them (Daily et al., 1997). They provide a wide variety of benefits that ranges between provisioning, regulating, supporting and cultural services, which stabilize climate, protect plants and animal species, provide food and shelter to local communities, protect critical human infrastructure such as settlements, roads, and railway lines from gravitational natural hazards, and isolate large amount of carbon as a result of recycling of gases (Millenium ecosystem assessment 2005, Bonan 2008, Gamfeldt et al., 2013). These functions, as the deal with other nature's services, have also been claimed to be of great economic value (Costanza et al., 1997, Pearce et al., 2001). Unfortunately, in most cases, forests are unsustainably managed, resulting in the "mining" of the forest resource and widespread ecological degradation (Barnes et al., 1997). It is critical that in the future, all forest uses are conducted in a manner that is more responsible in terms of sustaining the resource.

In this context, sustainable forest management can be defined as the use of forest resources in a way and at a rate that maintains their biodiversity, productivity, regeneration capacity, and their potential to fulfill now, and in the future, the relevant ecological, economic and social functions (Martin-Garcia and Diez 2012). However, while sustainable forest management, seen as a constant yield of wood supply, has been practiced in forestry for centuries, modern ideas of sustainability are broader in scope, embracing all the goods and services of the forest. And as a result, forests are increasingly being managed as multifunctional ecosystems (Farrell et al., 2000). Therefore, forests are viewed as complex social-ecological systems (SESs), requiring adaptive and multifunctional management (Messier et al., 2015). In this context, forest multifunctional management, which highlights the ecological and economic characters of forests, has become a fundamental objective for several European countries (e.g., France, Italy, and Germany) (Slee 2012).

Recent movements in sustainability science for forest SESs acknowledged the key role of infrastructures. For example, Anderies et al. (2019) argues the importance of infrastructures in obtaining knowledge over how actions can manipulate and impact SESs, while Oberlack et al. (2015) attributed the regrowth of forests in the tropics to the presence of robust community institutions and co-management between communities and national government. Nonetheless, the capacity of societies to address forest sustainability hinges on their extent to deal with several social dilemmas associated with integrating their activity and cooperating with respect to multiple uses of the forest as well as provisioning shared human-made infrastructure (Muneepeerakul and Anderies 2017, Houballah et al., 2018). Anderies et al. (2004) developed a framework (robustness framework) that combines the social and ecological facet around the concept of infrastructures. In this framework, infrastructures are broadly defined to include natural and human-made infrastructures that enable the operation of societies (Anderies et al., 2016). In the same vein, Clark et al. (1979) investigates the connection between sustainability of resource systems and management of infrastructures and present an example on how investments in fishing boats can be of impactful effect on the dynamics of fisheries SES. Therefore, planning for sustainable and multiple-use management of a forest resource can be enhanced through decisions of investment in a shared and multifunctional road network (Houballah et al., 2018).

Constructing and maintaining multifunctional forest roads are considered key elements for successful forest management. However, trade-offs between these two elements have negative and positive effects on different forest functions, which induces complexity in the decision-making process. For example, building a lot of forest roads can increase accessibility to the forest which benefits wood extraction but can negatively affect the scenic beauty as well as the biodiversity of the forest (Li et al., 2013). In this context, Houballah et al. (2018) considered a new approach that combines the SES and robustness frameworks to present a new perceptive for understanding interactions in multifunctional forest management through infrastructural point of view (see fig. 1-a).

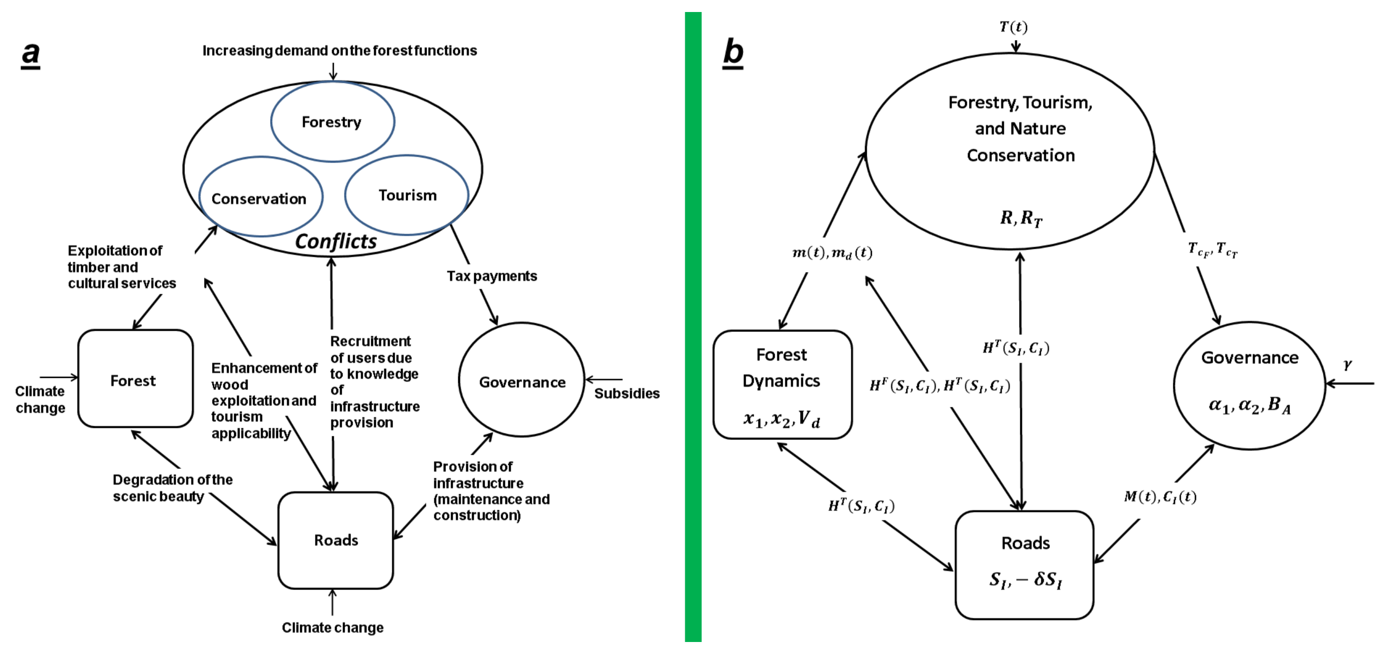


Figure 1. (a) Represents the robustness framework adapted to the forest's functionalities. (b) Represents the diagram of the operationalization of the robustness framework that summarizes the model. Functions produce $m(t)$ (wood harvesting), $m_d(t)$ (deadwood harvesting) resource units from the forest which produce x_1 (big trees), x_2 (small trees) and V_d (deadwood volume). Functions generate revenue R, R_T which contribute a proportion T_{c_F}, T_{c_T} to the governance that, in turn, choose to allocate proportions α_1, α_2 from the total budget B_A to maintaining roads ($M(t)$), constructing roads ($C_I(t)$) respectively. Thus, the governance produces and maintains the infrastructure stock C_I, S_I subject to depreciation dynamics $-\delta S_I$. S_I and C_I enhances the productivity of the timber RUs through $H^F(S_I, C_I)$, and the infrastructural attractiveness of the forest through $H^T(S_I, C_I)$ that enhances tourism by attracting more tourists $T(t)$.

To fully integrate the role of shared infrastructures and their governance into ecosystem science, we propose a generic conceptual modeling approach, based on Houballah et al. (2018) study that links human and biophysical drivers, patterns, processes, and effects. Our main contributions are (1) development of a theoretical – but informed by a real case study – mathematical model that operationalizes the modified robustness conceptual framework of figure (1-a) to analyze the interactions in a multifunctional forest management; (2) the study of the multifunctional forest management through analyzing the multi-functionality of road infrastructure; and finally (3) define an index of multi-functionality as way to quantify the performance of forest multifunctional management where we study the potentialities and strategies for fostering forest multi-functionality. In particular, our study analyzes the three different forest functions (wood production, tourism, and nature conservation) and related governance strategies through the lens of the robustness framework and brings to clear focus, using mathematical expressions, the interactions between diverse forest functions, multi-functionality of road infrastructure, dynamics of the forest, and governance influence.

Modeling FOREST MULTI-FUNCTIONALITY

2.1 INTRODUCTION

The model construction is inspired by a real case study (Houballah et al., 2018). The Quatre-Montagne has about 17000 ha of forest cover. Changing socioeconomic factors have led to a suite of land-use changes in forested areas, and significant changes in some ecosystem services (Parmentier 2013). There are three forest functions that are considered as major economic and social drivers of exploitation, wood removal, tourism, and nature conservation. However, due to the mountainous terrain, these functions face particular difficulties linked to the accessibility of the resource (Avocat et al., 2011). In their approach, Houballah et al. (2018) introduced a systematic conceptualization of the multifunctional forest management in the Quatre-Montagne forest by connecting functions to relevant infrastructures. The methodology consisted in applying Ostrom's SES framework (Ostrom 2009) and then connect function-specific framework variables to relevant infrastructures, in which they study them through the robustness framework.

In this article, we base our model construction on the study found in Houballah et al. (2018) to analyze the interaction of governance and the forest through infrastructures and the capacity of the system to withstand disturbances. In particular, we use the modified robustness framework (cf. fig. 1-a) to guide the development of the model and the analysis. We then explore the relationship between forest functions mentioned above (wood production, tourism, and nature conservation) and the ecosystem. Moreover, we examine the relation between functions performance and governance by delving into the role of governance in providing infrastructure (by which functions gain affordances to exploit). Figure (1-b) shows how we operationalize and adapt the robustness framework to help organize the presentation of the model and serve to answer our particular set of questions. We mention that even though the model is based upon a real case study analysis; assumptions, analysis, and choice of parameters remain purely theoretical. All parameters of the model and their values are defined and outlined in the table (S1) found in the appendix.

2.2 FOREST DYNAMICS

The forest growth model has been developed and analyzed in Mathias et al. (2015) and has been modified to fit our analysis. We consider monospecific silver fir stands and a 1 ha representative sample of each user's forest stand. The stand is composed of two strata, the upper stratum x_1 (big trees) and the lower stratum x_2 (small trees) at time t. We also consider that only trees in the upper stratum are removed for wood production.

The dynamics of stratum 1 in the forest is assumed to be:

$$\frac{dx_1}{dt} = \overbrace{hx_2(t)(1 - ug_1x_1(t))}^{growth} - \overbrace{x_1(t)d}^{mortality} - \frac{\overbrace{m}^{removal}}{v_1}$$

Where:

- h is the intrinsic rate of the growth from stratum 2 to stratum 1
- u is the asymmetric competitive effect of stratum 1 on stratum 2
- g_1 is the mean basal area of trees in stratum 1
- d is the intrinsic mortality in stratum 1
- v_1 is the mean volume of trees in stratum 1
- m is the timber removal function which will be given later;

The dynamics of stratum 2 in the forest is assumed to be:

$$\frac{dx_2}{dt} = \overbrace{bg_1x_1(t)\big(1 - s(g_1x_1(t) + g_2x_2(t))\big)}^{recruitment} - \overbrace{hx_2(t)(1 - ug_1x_1(t))}^{growth} - \overbrace{x_2(t)(zg_1x_1(t) + d)}^{motality}$$

Where:

- b is the intrinsic recruitment rate
- s is the recruitment sensitivity to light interception by strata1 and 2
- g_2 is the mean basal of trees in stratum 2
- z models the mortality process in stratum 2 due to asymmetric competition

The volume of deadwood is considered a relevant indicator of biodiversity (Lassauce et al., 2011, Bouget et al., 2012). Decaying deadwood provides habitats for small vertebrates, invertebrates, and other Saproxylic species. Therefore, we introduce the deadwood volume dynamics as an indicator for the biodiversity of the forest and therefore, the nature conservation function. The total deadwood dynamics can be expressed by the following equation:

$$\frac{dV_d}{dt} = \overbrace{v_2x_2(t)(zg_1x_1(t) + d)}^{lower\ stratum\ mortality} + \overbrace{(m)(1 - p_e)}^{debris\ from\ removal} - \overbrace{(m_d)}^{deadwood\ removal} + \overbrace{v_1x_1(t)d}^{mortality} - \underbrace{\alpha V_d(t)}_{decomposition}$$

Where:

- v_2 is the mean volume of trees in stratum 2
- p_e is the ratio of tree volume that is effectively exported (in the case of whole tree extraction for wood energy, p_e is 1)
- m_d is the deadwood removal function and will be given later
- α is the rate of decay of deadwood

We consider that forest managers can partially control the wood harvest volume m, m_d (since the harvest is controlled by managers and augmented by infrastructures). They generate decisions based on their economic objective, forest welfare, and biodiversity incentive (deadwood volume). The user harvest functions are considered to be enhanced by infrastructures in the forest and can be expressed as follows:

$$m = h_m \times H^F(S_I, C_I)$$

$$m_d = o \times (v_1 x_1 d p_e) p_a \times H^F(S_I, C_I)$$

Where:

- h_m is the wood removal objective
- o is the ratio of deadwood removal per one road unit
- p_e is the ratio of timber volume that is effectively exported (in the case of whole tree extraction for wood energy, p_e is 1)
- p_a is the ratio of dead trees in stratum 1 that are removed for commercial purposes
- $H^F, S_I(t)$, and $C_I(t)$ are the road enhancement function, road state dynamics, and road constructions dynamics respectively that will be introduced later

The financial aspect of forest managers can be expressed as a function of the yield from the harvest subtracted by the cost of the effort exerted by the manager. The revenue function of the users can be expressed by the following equation:

$$R = ((p - c_m) \times m + (p_d - c_d) \times m_d) \times \left(1 - T_{c_F}\right)$$

Where:

- p is the price of one m^3 of timber (in euros);
- c_m is the cost for extracting one m^3 of timber;
- p_d is the price of one $m^3$of deadwood;
- c_d is the cost of extracting one $m^3$of deadwood;
- T_{c_F} is the ratio of taxes taken from forestry users (both for timber and deadwood harvest);

The innovation introduced in this model is the idea of linking the timber harvesting in the forest to the provisioning of roads.

2.2 TOURISM DYNAMICS

The tourism industry has increased considerably in recent decades and has become one of the main sources of income in many countries (Williams and Shaw 1988, Nijkamp and Coccossis 1995) and especially in the Vercors (FORGECO 2014, ARANGE 2015, Houballah et al., 2018). This development in the Vercors has been attributed to the scenic beauty of the mountainous terrain (FORGECO 2014, Tenerelli et al., 2016). For many tourist sites, the reward phase of development is characterized by long and intense growth in infrastructure and facilities. In fact, some destinations, after flourishing for a long time, have been abandoned by tourists in favor of more attractive sites newly available on the market (Butler 1991). In order to compensate for this instability, local agents may seek increased investment and develop special facilities to attract tourists. Sometimes they are successful, but at the expense of the forest environment and its functionality where it may be severely degraded.

The dynamical model of tourism we propose here represents the "outside social demand" on the forest and we consider that tourism, as a forest function, is measured according to the number of tourists the forest can attract. This model is not thoroughly based on data, but on very simple assumptions inspired by Casagrandi and Rinaldi (2002). These assumptions include interactions between three important components of the coupled system: the tourists, environment, and infrastructures that are based on so-called minimal models that are used to predict economic and environmental impact of any given policy (Anderies 2005).
Imagine that tourists are asked to report on the attractiveness of the forest, A, and let us assume that these reports influence the decisions of potential new visitors (spread of information; Morley 1998). Measuring A in a suitable unit, we can then write the rate of change of tourists at a given site is equal to the product TA, i.e.,

$$\frac{dT(t)}{dt} = T(t) \times A(T, E, H^T),$$

Where E is a function describing the attractiveness of the forest's environment, and H^T that of infrastructures. A refers here to relative attractiveness, namely the difference between the absolute attractiveness, $\hat{a}$, of the site (for which information on $T, E,$ and H^T is available) and a reference value, a, which can be thought of as the expected attractiveness of a generiµ c site (i.e., the average value of the attractiveness of all potential tourist sites). Thus

$$A(T, E, H^T) = \hat{a}(T, E, H^T) - a$$

Where a is influenced by a number of factors, including the price of alternative sites. In an abstract sense, a is a measure of competition exerted by alternative tourist sites on the forest. The attractiveness of the site, being perceived by tourists, depends upon their sensitivity to the quality of the natural environment and their ability to detect it. It is the algebraic sum of three terms (1) environmental quality, (2) availability and state of infrastructure, and (3) congestion of tourists. We consider here that the environmental attractiveness is affected by the forest structure where uneven-aged stands are considered most suitable for tourism in both winter and summer seasons. Which can be summarized by a minimum and maximum amount of trees in the forest (continuous cover) and a minimum ratio between trees of the two strata (structural complexity) Thus to describe the quality of the forest environment, we consider the following function (see fig. 2):

$$E(x_1, x_2) = f(x_1, x_2)$$

Such that f is a 2-d Gaussian-like function:

$$f(x_1, x_2) = exp(-(\omega_1(x_1 - x_1^0)^2 + 2\omega_2(x_1 - x_1^0)(x_2 - x_2^0) + \omega_3(x_2 - x_2^0)^2))$$

Where:

- x_1^0, x_2^0 are the assumed forest most attractive structure for tourists
- $\omega_1, \omega_2, \omega_3$ are the rate of change of the forest attractiveness

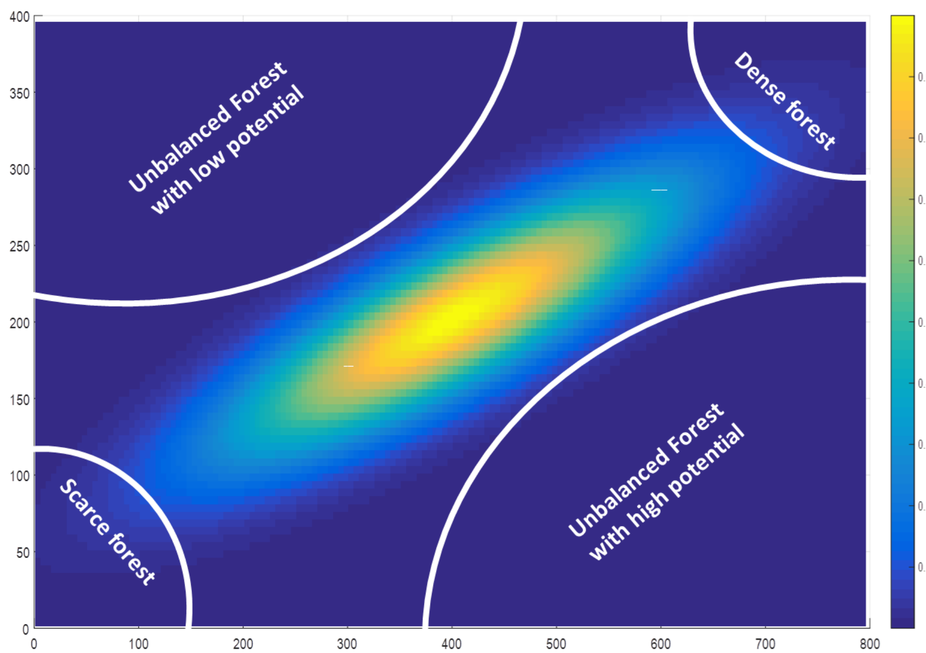


Figure 2. Environmental attractiveness function (E) **with** $0 < Strata\ 1\ of\ big\ trees < 400\ ha^{-1}$ **and** $0 < Strata\ 2\ of\ small\ trees < 800\ ha^{-1}$**, where** $x_1^0 = 200\ ha^{-1}$ **and** $x_2^0 = 400\ ha^{-1}$.

Finally, we assume that the congestion is proportional to T and that attractiveness is linearly decreasing with congestion, we end up with the following dynamics for T:

$$\frac{dT}{dt} = T[\overbrace{\hat{a}(T,E,H^T)}^{absolute\ attractiveness} - \overbrace{\bar{a}}^{expected\ attractivenss}]$$
$$= T[\overbrace{\bar{E}}^{attractivenss\ of\ the\ environement} + \overbrace{H^T(S_I,C_I)}^{attractiveness\ of\ the\ infra.} - \overbrace{\alpha_T T}^{congestion} - \underbrace{a}_{competetion}]$$

Where:

- α_T the ratio of congestion of tourists
- a is the expected attractiveness of the forest
- $H^T(S_I,C_I)$ will be given later as the attractiveness function that depends on the availability and state of roads

We consider that the revenue function (economic indicator) for the tourism industry in the forest is a ratio of the number of tourists in the area. Indeed, Stynes (1997) argues that one of the criteria to assess economic output for tourism is derived from the measure of the number of tourists at the site. For example, an increase of tourists staying overnight in hotels would directly yield increased sales in the hotel sector. The additional hotel sales and associated changes in hotel payments for wages and salaries, taxes, and supplies and services are direct effects of tourism spending. Therefore we consider that a revenue function proportional to the number of tourism users can be expressed as follows:

$$R_T = \pi_T T(t) \times (1 - T_{c_T})$$

Where:

- π_T is the proportion of the money paid by the tourism users
- T_{c_T} is the ratio of taxes taken from tourists to the government

2.3 ROAD INFRASTRUCTURE ENHANCEMENT FUNCTIONS

$H^F(S_I,C_I)$ is the function that maps S_I and C_I to the productivity of users and is inspired by Muneepeerakul and Anderies (2017). Many shared infrastructures exhibit non-linear behavior in their productivity. For example, once the state of forest roads become so poor that it falls below a certain threshold, one that is related to major road blockage, the road's employment in accessibility stops working. Moreover, the productivity of users is linked as well to the availability of infrastructure. Therefore, to capture such behavior, we assume the following piecewise function for $H^F(S_I(t),C_I(t))$:

$$H^F(S_I(t),C_I(t)) = \begin{cases} 0, & S_I(t) < S_{I_0} \\ C_I(t)\dfrac{S_I(t) - S_{I_0}}{S_{I_m} - S_{I_0}}, & S_{I_0} \le S_I(t) \le S_{I_m}, \\ C_I(t), & S_I(t) > S_{I_m} \end{cases}$$

Where:

- S_{I_0} is the threshold of S_I below which H^F is zero
- S_{I_m} is the threshold of S_I above which H^F is maximum regarding the quality of available roads

$H^T(S_I(t), C_I(t))$ is the function linking S_I and C_I to infrastructure attractiveness. It is considered that for a certain amount of roads the perception of tourists regarding the area's attractiveness is considered to be the highest, after this value the perception starts declining due to the "congestion of infrastructure". While infrastructures are of importance for the development of tourism, we also consider that its congestion negatively affects the natural scenic beauty of forests (Pastorella et al., 2016). For example, Thiel et al. (2008) concluded that infrastructures should be limited in certain forest areas to retain undisturbed forest patches within skiing areas. To capture the behavioral effect of tourists to infrastructure attractiveness, we assume the following Gaussian piecewise like function:

$$H^T(S_I, C_I) = \begin{cases} 0, & S_I < S_{I_{0T}} \\ a_T e^{-\frac{(C_I - C_{I_{0T}})}{2c_T^2}} \dfrac{S_I - S_{I_{0T}}}{S_{I_{mT}} - S_{I_{0T}}}, & S_{I_{0T}} \le S_I \le S_{I_{mT}} \\ a_T e^{-\frac{(C_I - C_{I_{0T}})}{2c_T^2}}, & S_I > S_{I_{mT}} \end{cases}$$

Where:

- a_T is the maximum attractiveness related to road availability
- $C_{I_{0T}}$ is the number of roads in which the perception of tourists is considered the highest
- C_T is the rate of increase/decrease of roads attractiveness when the number of roads increases
- $S_{I_{0T}}$ is the threshold of S_I below which the attractiveness associated with the quality of infrastructure is zero
- $S_{I_{mT}}$ is the threshold of S_I above which the attractiveness associated with the quality of roads is maximum with respect to available roads

2.4 ROAD INFRASTRUCTURE DYNAMICS

For the sake of simplicity, we consider that all types of roads in the forest are used for all forest functions. On one hand, governance in the forest can decide to introduce new roads as a part of a strategy for increasing accessibility in the forest; this decision is based upon its measured effectiveness as well as the amount of money allocated for that purpose. In order to define a system of road network development, we first consider (1) the idea that existing roads trigger development of more in and (2) the forest, being a finite space, can only withstand a maximum number of road units. Therefore, the dynamics of the number of road unit measured in $km\ ha^{-1}$ in the forest can be expressed by the following logistic growth equation:

$$\frac{dC_I(t)}{dt} = \overbrace{(\alpha_1 \times I_{BA} \times B_A(t) \times u_1 \times \mu)}^{Growth} \times C_I(t) \times (1 - \frac{C_I(t)}{C_{I^{max}}}),$$

Where:

- α_1 is the portion of the annual budget $(I_{BA} \times B_A(t))$ allocated for constructing roads
- u_1 is the effectiveness of investment in constructing roads
- $C_{I^{max}}$ is the maximum carrying capacity for the number of road unit in the forest
- μ is the growth in $CI(t)$ per unit of road

On the other hand, governance is responsible for maintaining the road infrastructure in the forest, the behavior of such action is mediated by the amount of money allocated from the annual budget of the governance as well as the effectiveness of such action. Moreover, maintenance is reduced by the increasing number of road units as the effectiveness of the maintenance budget becomes less efficient. The function of maintenance can be expressed by the following equation:

$$M(t) = \alpha_2 \times I_{BA} \times B_A(t) \times (\overbrace{u_2 \quad \times \quad \frac{1}{C_I(t) + k}}^{effetiveness\ decreased\ by\ the\ increased\ C_I(t)})$$

Where:

- α_2 is the portion of the annual budget $(I_{BA} \times B_A(t))$ allocated for maintaining roads
- u_2 is the effectiveness of investment in maintaining roads
- k is the rate of decrease in road maintenance effectiveness

Maintenance of infrastructure is seen as a logistic growth of a road state dynamic. In particular, at low state the growth is considered little due to the poor conditions of roads (using roads to maintain other roads), however, the growth increases with the increase of the state until it reaches very high quality and becomes costly to maintain. Moreover, introducing a new road has a positive effect on the state dynamics, where the newly built roads are considered to have maximum quality, and however, negatively affected by the depreciation effect. The dynamics of the state of roads $S_I(t)$ is described as follows:

$$\frac{dS_I(t)}{dt} = \overbrace{M(t) \times S_I(t) \times (1 - S_I(t))}^{maintenance} + \underbrace{\frac{\varepsilon(S_{I_m} - S_I(t))}{C_I(t)}}_{effect\ of\ introducing\ a\ new\ road} - \overbrace{\delta S_I(t)}^{depreciation}$$

Where:

- δ is the infrastructure's depreciation rate.
- ε is the number of roads introduced at time t.

2.5 GOVERNANCE OF INFRASTRUCTURES

Our analysis focuses on understanding the nature of the economic and political governance from an infrastructural point of view and within the dynamics of the robustness framework. In this context, governance (or public infrastructure providers in the robustness framework) in the forest is highlighted by the ability to provide public shared infrastructure.
The behavior of governance is manifested in the amount of resources collected from the forest functions that are appropriated by the governance for maintaining and constructing roads in the forest. The annual budget (B_A) of the governance is composed of taxes (T_{c_F}, T_{c_T}) paid by forest users (timber and tourism users), as well as subsidies (γ), paid either by the French government or the European Union for forest management in the Western Alps, and is given by the following equation:

$$B_A(t) = \overbrace{T_{c_F}}^{forestry\ tax\ contribution\ ratio} \times \left(\overbrace{m(t) \times (p - c_m)}^{revenue\ of\ timber\ harvest} + \overbrace{m_d(t) \times (p_d - c_d)}^{revenue\ of\ deadwood\ harvest} \right) + \overbrace{\pi_T T(t)}^{revenue\ from\ toursim\ function} \times \overbrace{T_{c_T}}^{tourism\ tax\ contribution\ ratio} + \overbrace{\gamma}^{subsidies}$$

2.6 COUPLED DYNAMICS

Before proceeding with the results of the model, let us recall that we are analyzing the following system of six differential equations:

$$\frac{dx_1}{dt} = \overbrace{hx_2(1 - ug_1x_1)}^{growth} - \overbrace{x_1d}^{mortality} - \overbrace{\frac{h_m \times H^F(S_I, C_I)}{v_1}}^{removal}$$

$$\frac{dx_2}{dt} = \overbrace{bg_1x_1\big(1 - s(g_1x_1 + g_2x_2)\big)}^{recruitment} - \overbrace{hx_2(1 - ug_1x_1)}^{growth} - \overbrace{x_2(zg_1x_1 + d)}^{mortality}$$

$$\frac{dV_d}{dt} = \overbrace{v_2x_2(zg_1x_1 + d)}^{lower\ stratum\ mortality} + \overbrace{(h_m \times H^F(S_I, C_I))(1 - p_e)}^{debris\ from\ removal} - \overbrace{(o \times v_1x_1dp_ep_a \times H^F(S_I, C_I))}^{Deadwood\ removal} + \overbrace{v_1x_1d}^{mortality} - \underbrace{\alpha V_d}_{decomposition}$$

$$\frac{dT}{dt} = T[\overbrace{E}^{attractivenss\ of\ the\ environement} + \overbrace{H^T(S_I, C_I)}^{attractiveness\ of\ the\ infra.} - \overbrace{\alpha_T T}^{congestion} - a]$$

$$\frac{dS_I(t)}{dt} = \overbrace{M(t) \times S_I(t) \times \big(1 - S_I(t)\big)}^{maintenance} + \underbrace{\frac{\varepsilon\left(S_{I_m} - S_I(t)\right)}{C_I(t)}}_{effect\ of\ introducing\ a\ new\ road} - \overbrace{\delta S_I(\mathrm{t})}^{depreciation}$$

$$\frac{dC_I(t)}{dt} = \overbrace{(\alpha_1 \times I_{BA} \times B_A(t) \times u_1 \times \mu)}^{Growth} \times C_I(t) \times (1 - \frac{C_I(t)}{C_{I}max}),$$

The model analysis reveals a rich set of results that highlights the interplay and trade-offs between forest functions mediated by the resource dynamics as well as infrastructure characteristics and illustrate the emergence of sustainability and multi-functionality of forests in an infrastructure mediated context. The overall picture that guides our analysis is that forest functions are mediated by the availability and state of shared accessibility infrastructures. This offers governance control on the exploitation of the forest where it can severely impact the multifunctional management and consequently the resource's sustainability.

RESULTS

For the following scenario simulations, we use Euler implementation in Matlab with a *0.1* time step to solve our coupled system using the parameter values given in table S1 (see appendix). In the subsequent discussions, we consider that users of different functions are maximizers of benefits in the sense that they don't care about damaging and degrading other functions. For example, timber harvest users only care about extracting wood regardless of the impact on the forest scenic beauty perceived by the tourists. In our simulations, we choose a 50 years' time span, which is not too much to be unrealistic and not too small for the analysis of trade-offs between forest functions. Moreover, to quantify the wood removal function, we take into account the annual wood extracted from tree cuttings and the deadwood collected from the forest. In our analysis, we define a collapse of the forest system as the dysfunctionality of the forest ecosystem services. In our simulations, we specifically address the following questions: 1) can the initial forest structure explain the preservation of forest functions whatever the investment strategies for infrastructures? 2) for what infrastructure strategies the different functions are maximized? 3) are there any trade-offs between the three functions investigated? and finally, 4) what are the governance strategies that have the potential to foster multi-functionality?

3.1 EFFECT OF INITIAL FOREST STRUCTURE ON FOREST FUNCTIONS

For the sake of clarity and comprehension of the model, we perform simulations first according to initial forest structures (x_1, x_2). Figure (3) shows the final value of simulations of the functions (wood removal "WR", tourism "T", and nature conservation expressed by a biodiversity indicator measured as the deadwood volume "DW" per ha) according to initial forest stand and a fixed investment from the governance for the construction and maintenance of roads (fig. 3, panel a→c). The figure shows also the evolution of the different system dynamics at three different points (A, B, and C) where functions have a change in behavior at their final values (fig. 3, panel d→i).

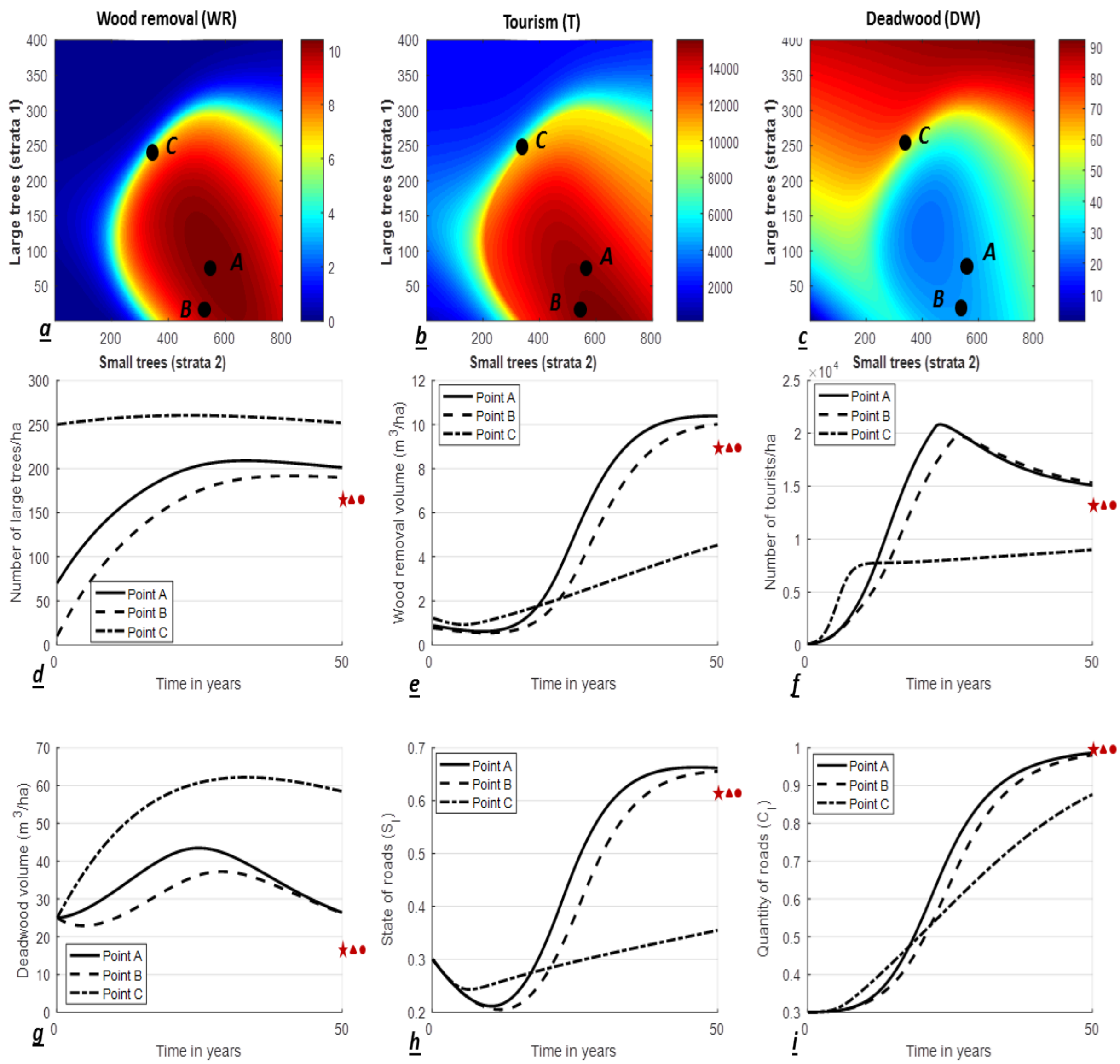


Figure 3. Panels (a→c) represent the final values of the forest functions simulation according to the initial forest structure, while panels (d→i) represent the simulation of the points A, B, and C. In all panels, the simulations were done on a 50 years' time horizon and according to an equal investment in roads construction and maintenance ($\alpha_1 = 0.5, \alpha_2 = 0.5$) and a tax ratio imposition ($T_{c_F} = 0.3, T_{c_T} = 1.5$). highlighted parameters are as follows: $h_m = 10$, $o = 2$, $C_I(0) = 0.3$, $S_I(0) = 0.3$, $x_1^0 = 200$, $x_2^0 = 400$, other parameter values can be found in table (S1) in the appendix. ★, ▲, and ● refer to the equilibrium state at points A, B, and C respectively.

As shown in the figure (3), panel a, on one hand when the number of trees at initial states in stratum 2 is not enough (insufficient number of small trees), the WR function undergoes a slow development and does not attain high values after 50 years (see point C). On the other hand, having a very high number of big trees incurs higher competition between the two strata which increases the small trees' mortality and moves the forest towards a lower potential state. However, the maximum value for WR attained in 50 years is when there is a high number of small trees at initial states (see point A), in other words, where we have an unbalanced forest with high potential. Furthermore, point B shows that wood harvest function levels slightly decreases in the initial forest structure which maximizes T. This is due to the big amounts of money that can accompany a high attraction of tourists (fig. 3, panel f), which leads to an over-investment in infrastructures and then a high extraction of wood and finally a slight change in the structure of the forest, which disfavors T. This chain of effects can be seen as a closed-loop negative process, which leads to a peak at early time and settles for a lower value at sustainable state.

Moreover, figure (3), panel (b) indicates that the number of tourists reaches its high values at high potential forest structure (see point B with a high number of small trees). This is due to the effect of WR on the forest, in which it moves its structure to a state that slightly favors T (see fig. 3, panels d and e). Such a behavior, with a relatively low $h_m = 10$ is a classic reaction of the compatibility of WR with T, where WR can help moving (through tree removal) the forest structure towards a favorable state.

Figure (3), panel (c) shows that at points A and B, where the T and WR functions are fairly high, DW is low; this can be explained thanks to the high annual budget that can be obtained from the two functions, which allows for the development of road infrastructure, and eventually a high extraction potentiality for deadwood. At point C, where there are a lot of big trees and small trees, T and WR slowly develop due to the gradual development of tourism in the area (fig. 3, panels e, f) which can be explained by the disadvantageous initial forest structure for the attractiveness function; this leads to a low annual budget, and therefore, low infrastructure investment. However, for the DW volume, and due to the low potentiality of extraction and the high ratio of tree mortality, the final value is maximized.

3.2 INFLUENCE OF GOVERNANCE

Accomplishing an objective of “harvesting more while preserving better” with achieving increases in WR, T, and biodiversity preservation (DW volume) requires improvements in governance of forest infrastructures. As explained before, our model can address this issue, and we propose here to analyze the effect of different infrastructure governance scenarios on the forest system at the equilibrium state. For this purpose, we test different approaches of infrastructure governance including different strategies of investment in maintenance and construction of roads ($0 < \alpha_1 < 1$ such that $\alpha_1 + \alpha_2 = 1$); and according to different actions of tax impositions ($0 < T_{c_F} < 0.4$ and $0 < T_{c_T} < 0.2$). Figure (4) presents the final value of forest functions according to these strategies for a fixed initial forest stand. Moreover, the figure displays the evolution of the different model dynamics according to three different points (A, B, and C) where functions reach completely different final values (fig. 4, panels d, e, f, g, h, i).

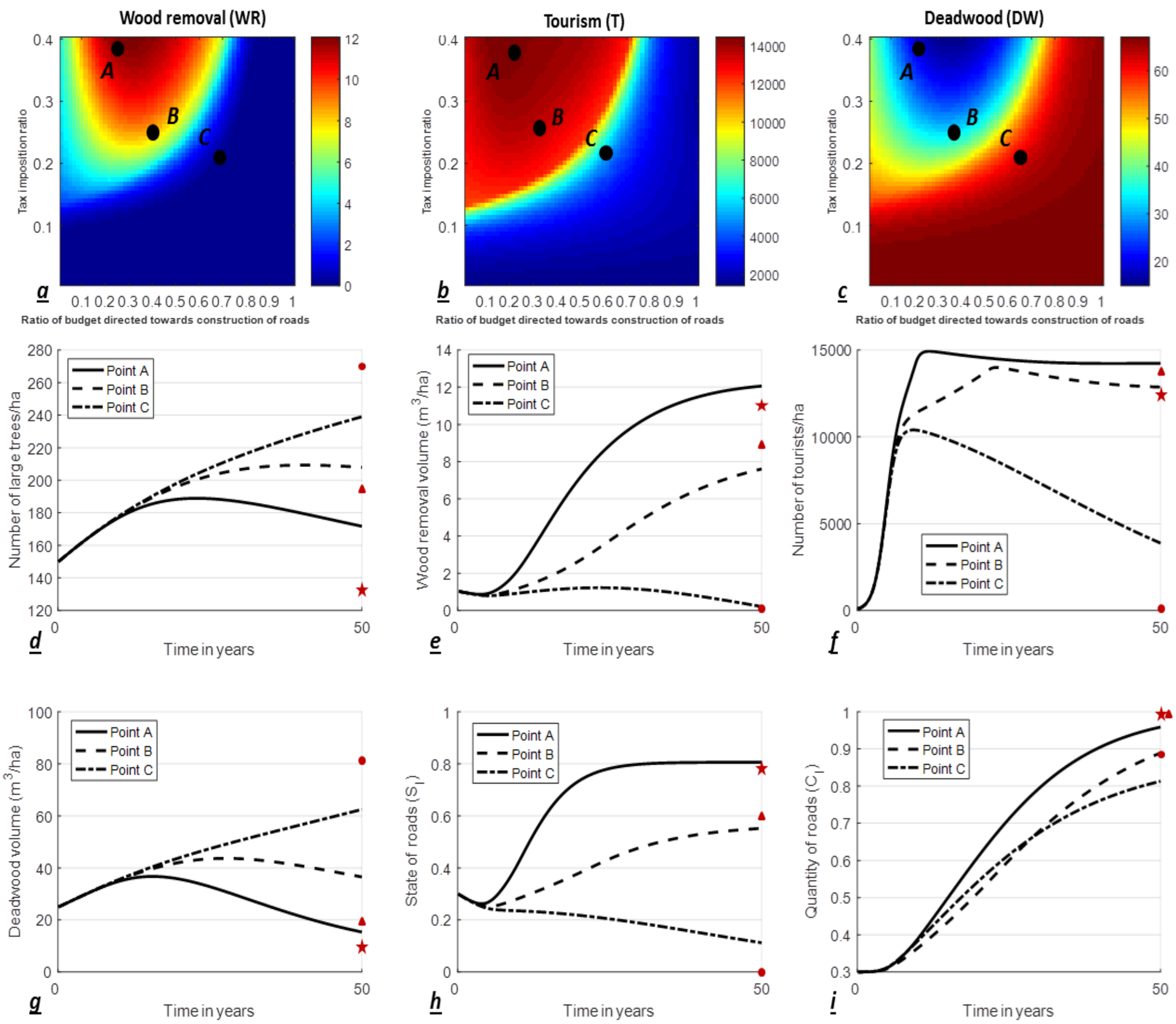


Figure 4. Panels (a→c) represent the final values of the forest functions simulation according to the strategy of investment in construction/maintenance, and the tax imposition ratio, while panels (d→i) represent the simulation of the points A, B, and C. In all panels, the simulations were done on a 50 years' time horizon for an initial forest structure $x_1(0) = 150$ and $x_2(0) = 300$. Other parameters are as follows: $h_m = 10$, $o = 2$, $C_I(0) = 0.3$, $S_I(0) = 0.3$, $x_1^0 = 200$, $x_2^0 = 400$. ★, ▲, and ● refer to the equilibrium state at points A, B, and C respectively.

Figure (4), panel (a) shows that when the ratio of budget directed towards construction of roads is very high (see point C), the functionality of the WR function decreases, this is due to the fact that over-investing in road construction takes money from the investment in maintenance of these roads, and on top of that, as roads increase it becomes very costly to maintain them. In other words, with governance strategies of high road construction and low maintenance investments, the roads cannot preserve their state and will lead to the loss of their employment in WR. Point A shows that for the right amount of road construction investment and sufficient tax ratio imposition, WR function can be maximized (fig. 4-e). But however, as point B shows, not enough investment in road maintenance can lead to slow development of WR function.

Moreover, figure (4), panel (b) represents T attraction in the forest and shows that the function is maximized with strategies that are directed towards maximizing wood extraction (with a low investment in road construction and high tax imposition, see fig. 4, panels f, e, i). In the area where wood extraction is maximized (point A), the tourism function is also maximized (fig. 4, panel f), this can be explained by the tree cutting effect on the structure of the forest which moves the forest to a more desired and attractive state. Furthermore, point C shows that high investment in road construction can cutback the infrastructure attractiveness and therefore gradually decrease the attraction of tourists (fig. 4, panels f, i). Finally, figure 4, panel (c) shows that for a governance strategy that is directed towards high WR (point A), the deadwood volume is decreased (fig. 4, panel e, g), while for a strategy directed at offering low potentiality for wood extraction (point B and C), one can observe an increase in the values of DW.

3.3 FOREST MULTI-FUNCTIONALITY WITH EXTREME CASES

As shown previously in simulations, one can observe evidence of slight trade-offs between forest functions. Thus, we choose to highlight these trade-offs by taking extreme cases with functions' objectives. For that, we consider the following two cases:

CASE OF HIGH WOOD EXTRACTION

In this section, we focus on an important issue in multifunctional forest governance that can help in highlighting the trade-offs that occur in a relatively short-term period (50 years). We choose a case where we have intensive WR levels ($h_m = 30\, m^3/\, ha,\ o = 3/[C_I]$). Although this case refers to an unsustainable outcome for the forest (see appendix), we are interested in the trade-offs that can occur in a relatively short-term period. Figure (5) presents the final value of forest functions according to these strategies for a fixed forest stand initial conditions. Moreover, the figure displays the evolution of the different model dynamics according to three different points (A, B, and C) where functions reach completely different final values (fig. 5, panels d, e, f, g, h, i).

As the case in section 3.2, Figure (5), panel (a) shows that when the ratio of budget directed towards construction of roads is very high (see point C), the functionality of the WR function decreases, while point A maximizes the function with the right strategies. However, with high WR objective, the area of strategies that maximize it increases, which indicates flexibility in the governance decision making.

Moreover, figure (5), panel (b) presents the tourism attraction in the forest and shows that the function is maximized with strategies that are not directed towards maximizing WR (with a low investment in road construction and relatively low tax ratio, see fig. 5, panels f, e, i). In the area where WR is maximized (point A), T function gradually decreases (fig. 5, panel f), this can be explained by the tree cutting effect on the structure of the forest which degrades its scenic beauty. Furthermore, point C shows that high investment in road construction can degrade the infrastructure attractiveness and therefore gradually decrease the attraction of tourists (fig. 5, panels f, i).

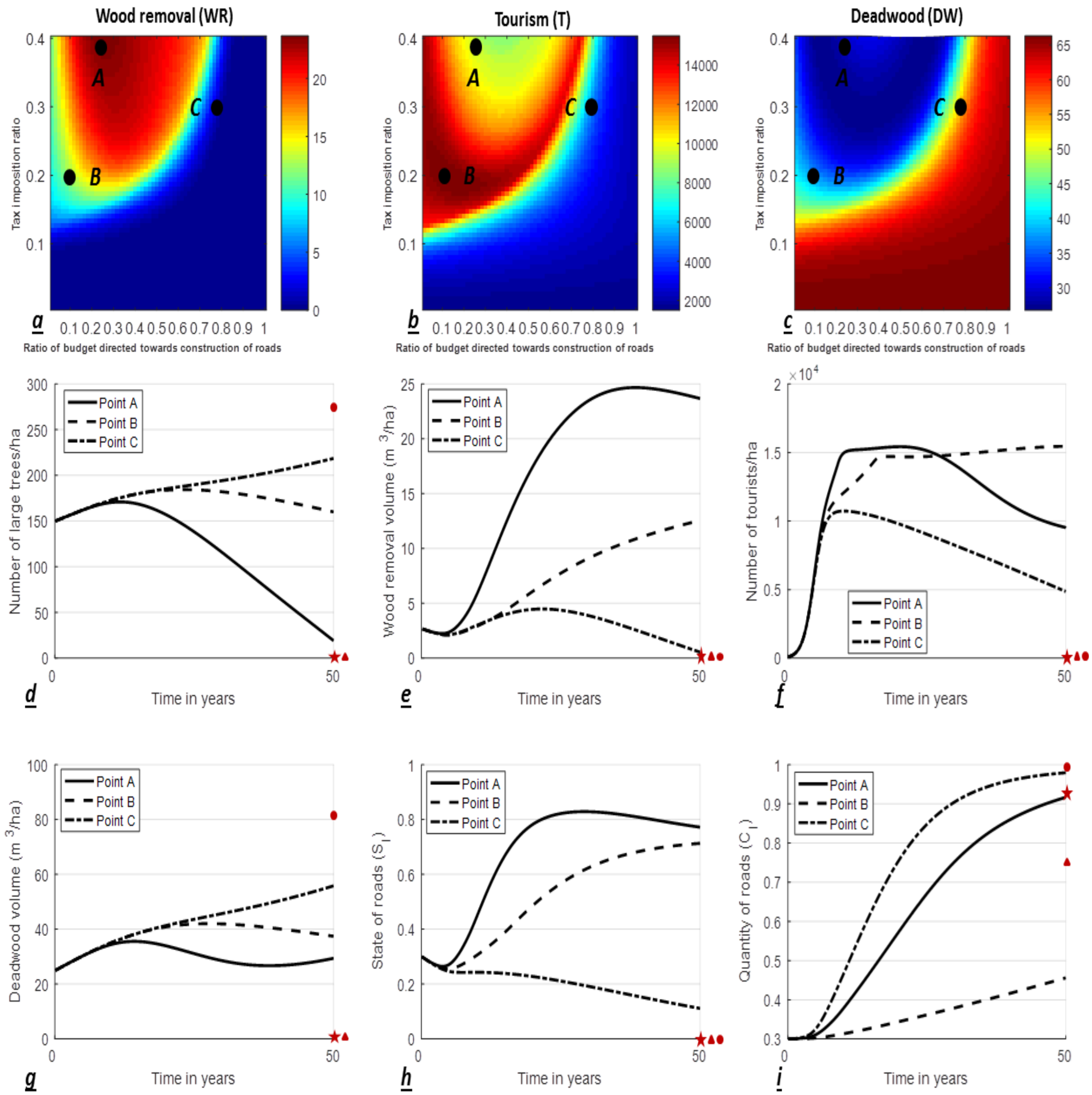


Figure 5. Panels (a→c) represent the final values of the forest functions simulation according to the strategy of investment in construction/maintenance, and the tax imposition ratio, while panels (d→l) represent the simulation of the points A, B, and C. In all panels, the simulations were done on a 50 years' time horizon for an initial forest structure $X_1{}^0 = 150$ and $X_2{}^0 = 300$. Other parameters are as follows: $h_m = 30, o = 3, C_I(0) = 0.3,\ S_I(0) = 0.3, x_1^0 = 200,\ x_2^0 = 400, \alpha_T = 5 \times 10^{-5}$. ★, ▲, and ● refer to the equilibrium state at points A, B, and C respectively.

Finally, figure (5), panel c shows that for a governance strategy that is directed towards high WR (point A), DW is decreased (fig. 5 panels e, g), while for a strategy directed at offering low potentiality for WR (point B and C), one can observe an increase for DW. The results of the simulations focus on, and highlight the, many trade-offs in the performance of each forest service. Maximizing one function can incur negative effects on others. The governance, being an infrastructure provider, or in other words, offeror of potentiality for exploitation, play an important role in maintaining and developing the different functions without affecting the overall economic and ecological performance of the forest. In conclusion, a highly intensified forest with high wood extraction levels incurs negative effects on the performance of other functions, specifically tourism. In particular, such high levels of tree removal change the structure of the forest towards an unfavorable place for tourism negatively affecting it.

CASE OF HIGH TOLERANCE FOR TOURISM

In some cases of tourism management, decision-makers are able to consolidate, through some management strategy, the negative effect of congestion of tourists on the overall perceived attractiveness of the forest (i.e., by building more resorts). In this section, we suppose that we have tolerance towards tourists' congestion. We change the value of α_T to be 5×10^{-5}, and consequently, we simulate our model according to different infrastructures provision strategies. Figure 6 shows the evolution of the model in a high tourism tolerance environment.

The simulation suggests that tourism and wood extraction function development are compatible (point A, fig. 6, panel a). However, as fig. 6, panel (e) shows, even though we have a fast development of WR, this function is not sustainable in the long run, and the same goes for T (fig. 6, panel f). This is due to the fact that such high WR levels greatly affect the ability of the forest to sustain itself in the long term (fig. 6, panel d). Consequently, as a result of the fast augmentation in infrastructures, DW is extracted at high levels, which can explain its low abundance in the forest (fig. 6, panels c, g). This unsustainable behavior can be attributed to the peak in tourism function that increases the total annual budget, which enhances the provision of infrastructures augmenting wood removal, and finally affecting the sustainability of the forest;
Moreover, point B shows a slight decrease in T performance and a significant decrease in WR values. A slow development for road's state slightly restraints T function due to its effect on infrastructure attractiveness, but adequately limits WR values (fig. 6, panel a, e). This limitation on WR significantly accounted on one hand to a sustainable outcome for the forest by limiting its tree cutting (fig. 6, panel d) and on the other hand allowed for the feasibility of its functions (fig. 6, panels e, f, g).

Finally, point C accounts for mono-oriented function management directed towards DW. This strategy leads to a sustainable outcome for the forest (fig. 6-d) but nonetheless, drives its socio-economic functions (T and WR) towards an eminent dysfunction (fig. 6, panels e, f).

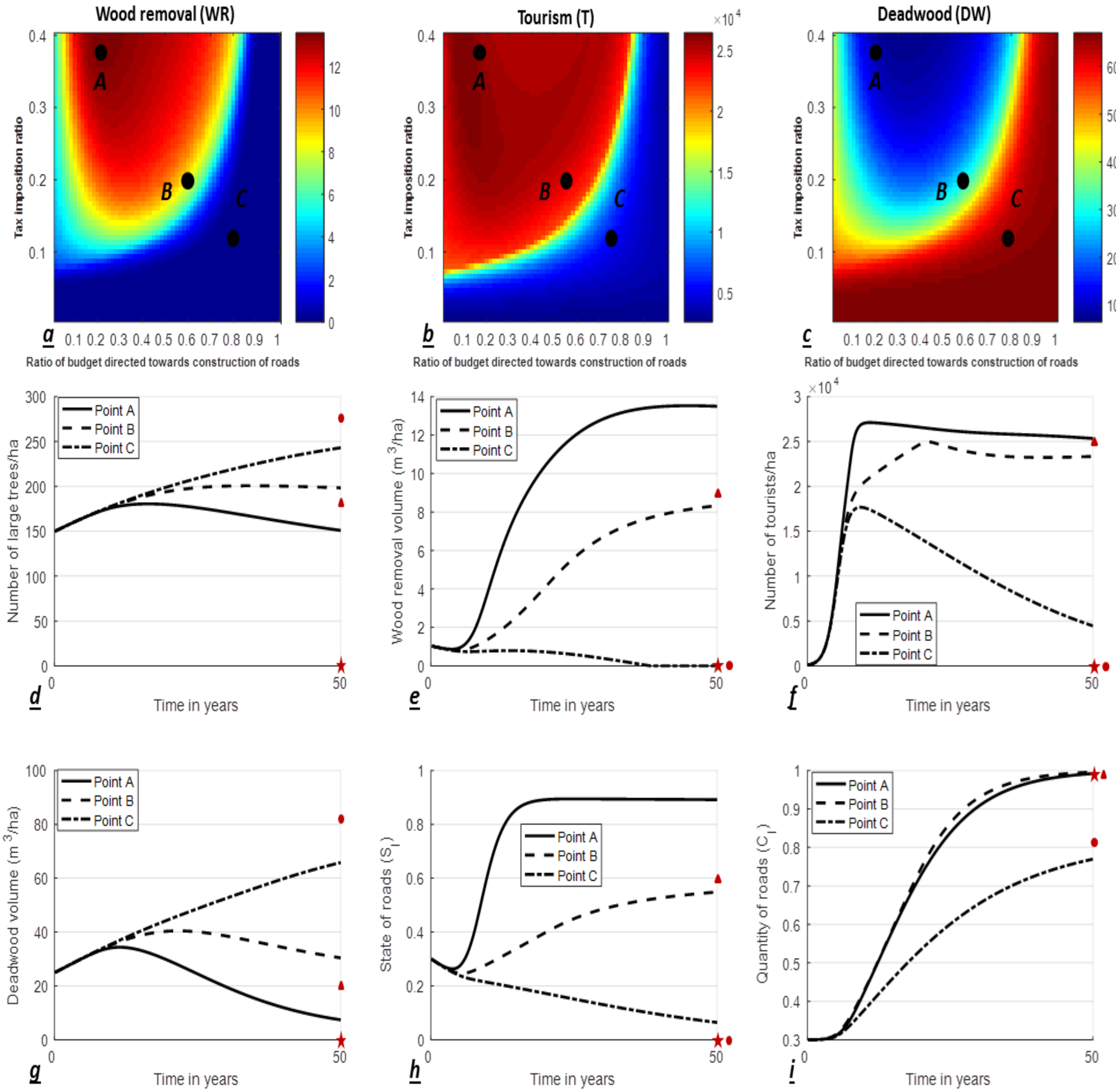


Figure 6. Panels (a→c) represent the final values of the forest functions simulation according to the strategy of investment in construction/maintenance, and the tax imposition ratio, while panels (d→i) represent the simulation of the points A, B, and C. In all panels, the simulations were done on a 50 years' time horizon for an initial forest structure $x_1(0) = 150$ and $x_2(0) = 300$. Other parameters are as follows: $h_m = 10$, $o = 2$, $C_I(0) = 0.3$, $S_I(0) = 0.3$, $x_1^0 = 200$, $x_2^0 = 400$, $\alpha_T = 5 \times 10^{-5}$. ★, ▲, and ● refer to the equilibrium state at points A, B, and C respectively.

3.4 MULTI-FUNCTIONALITY INDEX AS A TOOL TO MEASURE GOVERNANCE PERFORMANCE

With our presented model, we discuss the performance of multifunctional forest management from the perspective of each function, presenting the trade-offs and effects that interplays.

However, the model allows us to present a global multi-functionality index that is able to quantify the multifunctional management in forests. In this context, we define the multi-functionality index as follows:

$$MFI = k_1 WR_N + k_2 T_N + k_3 DW_N \qquad ()$$

Where WR_N, T_N, and DW_N represents the standardized values for wood removal volume, tourism, and deadwood volume respectively. $k_1, k_2,$ and k_3 are the weight parameters corresponding to WR, T, and DW respectively, that can explain the importance of one function in some forest's management context with:

$$k_1 + k_2 + k_3 = 1 \qquad ()$$

Figure (7) represents simulations of MFI for different cases (referenced, high wood extraction, and high tolerance for tourism) for different values of weights ($k_1, k_2,$ and k_3).

On one hand, in the cases where DW volume is not especially important (panels a1, a2, a3, b1, b2, b3, c1, c2, c3), *MFI* is confined in a relatively big set $[0.3\ 0.8]$; which indicates that decisions of governance in provisioning infrastructures are fairly important when it comes to fostering multi-functionality. For example, one decision can allow MFI to reach a high value of 0.8, while other decisions can drag its value to 0.3, which is not a proper governance of multi-functionality. Nonetheless, multi-functionality is maximized in the area that is beneficial for T and WR. On the other hand, in the case where DW is considered to be an important objective (panels d1, d2, d3), *MFI* is restrained in the set $[0.5\ 0.66]$, which indicates a lower effect of governance on its outcomes. MFI is maximized with governance strategy decisions that boost T and slightly decrease in the area that boosts WR. This is a clear presentation of the trade-offs between WR and biodiversity conservation.

Moreover, in all cases with WR oriented management, we observe a lower flexibility for the governance decision-making (with even lower flexibility in the high WR scenario). This behavior demonstrates the sensibility of the forest system towards wood removal. This is also backed up with the high WR scenario (panels a2, b2, c2, d2), where one can observe a lower performance of multi-functionality with strategies that maximize WR. Here multi-functionality management performance is significantly lowered highlighting the effects and interplays that can arise with socio-economic functions interactions.

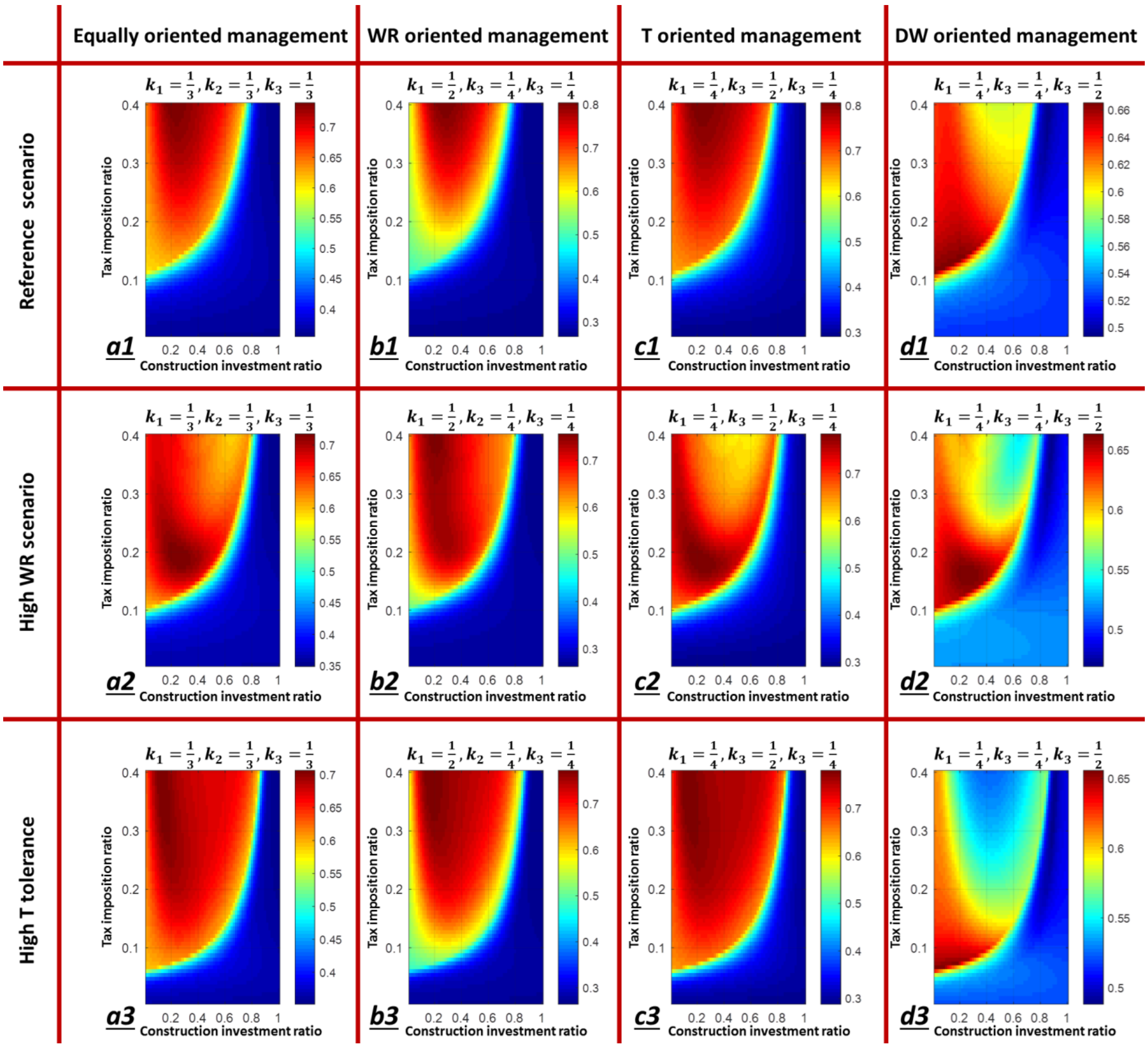


Figure 7. Illustration of the multi-functionality index (*MFI*) simulations according to different infrastructure provision strategies. Panels (*a1*→*d1*), (*a2*→*d2*), and (*a3*→*d3*) represents the simulation belonging to the reference case (section 3.2), high wood removal (WR) case (section 3.3.1), and high tourism (T) tolerance case (section 3.3.2) respectively. In all panels belonging to case scenarios, we simulate the multi-functionality index with different weight values (k_1, k_2, k_3).

DISCUSSION AND CONCLUSIONS

To address the problem of forest multi-functionality, we have mathematically operationalized the robustness framework conceptualization of forest multi-functionality based on Houballah et al. (2018) work. Here we consider a particular relation between forest functions and governance highlighted through their ability to provision infrastructures. Namely, the idea proposed here is that infrastructures provide potentiality for exploitation through accessibility needed either for tourism or wood removal. Naturally, such an assumption highlights the forest governance role in the development of ecosystem functions to meet the increasing demand of the market. We explored the extent of the model to represent the performance of the functions with simulations according to the forest's structure initial conditions and depending on different governance strategies for infrastructure provision in different extreme cases. Moreover, we have defined a multi-functionality index as a way of quantifying multifunctional forest management performance analyzing the different governance strategies in the present diverse extreme scenarios.

4.1 Trade-offs, interplays, and non-symmetric effects

Our findings highlighted the trade-offs and interplays that can occur between economic and social forest functions. In particular, our analysis gave a clear indication of the direct effect of wood removal on tourism and deadwood volume dynamics. This effect is backed up with the fact that wood removal, on one hand, can alter the structure of the forest and thus its scenic beauty, and ultimately affect the performance of tourism. On the other hand, through pursuing strategies that maximize wood removal, which falls in line with extracting more deadwood from the forest, it decreases the number of large trees that leads to reduce natural mortality in the forest. This ultimately affects biodiversity and nature conservation function. However, as shown from our analysis (see 3.3.1 and 3.3.2) the effect of tourism on wood removal is positive in a direct manner. In our model's context (Houballah et al., 2018), tourism permits the development of other functions by highly contributing to the annual budget directed towards infrastructure provision. Yet, through its maximization, it excessively enables wood removal, which can backfire on tourism and have dramatic consequences on the forest in the long run. These insights have been confirmed in previous studies that discuss synergies and trade-offs of ecosystem services. In particular, Stevens (2003) discusses the direct impact of deforestation on the performance of tourism as well as the reversible indirect effect of tourism on the wood removal function. Moreover, Lafond et al. (2017) confirmed our hypothesis concerning the negative effect of wood removal on deadwood dynamics (because of the deadwood harvest), and as our model shows, this effect is limited with the fact that wood removal of standing trees yields deadwood ($pe=0.9$, which refers to the ratio of tree being removed). Furthermore, Ahtikoski et al. (2011) notice the negative effect of removing trees on the structure of the forest with implications on recreational activities in forests. Lexer and Bugmann (2017) also reported strong trade-offs occurring between wood removal on one hand and other forest functions on the other hand in mountain forests.

4.2 Fostering multifunctional forest management

Many forest governance regimes have been, or are currently, shifting to multifunctional management mechanisms (La Notte 2008), aimed at improving the applicability of one function-sided management strategies in the presence of other functions in the forestry sector. With our analysis, particular attention is given to the role of management of infrastructures in giving potentiality for the development of forest functions. One obvious result that has been highlighted by our model is the need for careful planning of road provisions due to its immense effect on the biodiversity indicator (deadwood volume) (have also been concluded by other studies (Forman 2000, Loucks et al., 2003, Avon et al., 2010, Selva et al., 2011). Through the enablement of functions, roads can have a dangerous effect on the dynamics of deadwood volume affecting the biodiversity of the forest. Overall, our results confirm that roadless areas (Strittholt and Dellasala 2001, Freudenberger et al., 2013, Boston 2016) should be maintained to avoid negative effects on biodiversity and negative feedbacks on green tourism activities.

Nonetheless, fostering forest multi-functionality is a major problem in management where the simultaneous development of ecosystem functions is the focus (Shmithusen 2008). In a context where infrastructures play an important role in mediating the interactions between forest exploitation systems as well as its environment, we argue that on one hand, different infrastructure provision strategies can help reach a desirable outcome for forest multi-functionality. On the other hand, such strategies can reduce flexibility in decision-making for maximizing the performance of multifunctional forest management. Refining the optimal balance between these two processes should of paramount importance for future research.

As shown in sections 3.4, different infrastructure provision strategies may lead to different outcomes for multi-functionality index values. Figure (7) shows that in 50 years' time horizon the area where wood removal is maximized one can notice a slight decrease in the multi-functionality index, which shows a negative effect on the overall performance of the forest functions. Negative effects appear within the forest ecosystem through empowering wood removal (also verified by Lafond et al., 2017). Moreover, analysis of the figure suggests that to maximize the performance of multifunctional forest management, in our model's context, we have to minimize wood removal function as to the level that does not affect the perceived natural beauty of the forest (reported by several studies, Brown and Daniel 1984, Zhalnin et al., 2008, Klessig 2011). Moreover, in all cases where we have $k_3 = \frac{1}{2}$, the multi-functionality index is less sensitive to the governance strategies ($0.5 < MFI < 0.66$). This indicates that infrastructure provision strategy is less efficient for multi-functionality in cases where biodiversity is given higher priorities. Moreover, governance has lower flexibility for fostering multi-functionality in the scenario where we have a high objective of wood removal (Lexer and Bugmann 2017). In particular, the area which maximizes multi-functionality index in panels b1, b2, b3 (fig. 7) is relatively smaller, which reveals rigidity in decision making

4.3 Long-term and short-term infrastructure governance strategies

The results of the simulation focus and highlight the many tradeoffs in the functionality of each forest service. Maximizing one function can incur negative effects on the functionality of others. The governance, being an infrastructure provider, can play an important role in maintaining and developing the functions without affecting the overall economic, social, and ecological performance of the forest. In our simulations, we argue that a 50 years' horizon is considered to be realistic in a forest management context. However, trade-offs can occur between long-term and short-term governance strategies. On one hand, our analysis shows that a fast development of infrastructure, which accounts for a fast development of functions (short-term investment), can have influential effects on the long term sustainability (see sections 3.3.1 and 3.3.2; has also been reported by Bebbington et al., 2018, Alamgir et al., 2019). Following strategies that don't allow wood removal to have an effect on the forest structure may account for a sustainable outcome for the forest. On the other hand, following a long term strategy in the governance decision making may not be able to satisfy the current needs of the market rendering the governance strategy not ideal. In other words, the government has to consolidate, through infrastructure provision (or offering affordances for exploitation), the current needs of the market with the objective of long term sustainability of the forest.

4.4 Conclusion

Although our assumptions on the nature of infrastructures are fairly basic, the two functions $H^T(S_I, C_I)$ and $H^F(S_I, C_I)$, inspired by Muneepeerakul and Anderies (2017), defined a clear relationship between the ecosystem services and the biophysical environment of the forest. Moreover, such functions capture important aspects of infrastructures regarding the decision of exploitation (either functions use infrastructures for their benefit or don't). The idea that infrastructures can incur trade-offs among forest functions on one hand and between forest functional system and its ecosystem, on the other hand, can pose problems of management when trying to maximize one forest functions through the provision of infrastructure. Our model focuses on analyzing the forest multifunctional management through the provision of physical human-made infrastructure, which highlights the role of governance.

Our hope is that this work will contribute to the development of much-needed, systematic mathematical analysis of CISs, especially those focusing on multi-functionality concepts. Although our model is informed by a real case study, we believe that its analysis illustrates general dynamical features for forest functions and thus can be used in other contexts and for other systems; for instance, the derived results could serve as guidelines on how one might empirically measure multi-functionality in CISs. The nature of the model development adopted here was inspired by (Muneepeerakul and Anderies 2017), in which we believe it holds systematic value in resource modeling science. There is still value in improving the model with a better indicator for biodiversity that can potentially better highlight ecological trade-offs in the forest. Moreover, much work is also needed with the introduction of the concept of non-physical (or soft) infrastructures or "knowledge infrastructure" (Anderies et al., 2019) to the interplay between the forest functions and its ecosystem highlighting the adaptive management concept (Walters 1987). From a general standpoint, viability theory (Aubin 1991) can be useful in defining safe operating spaces (Rockstrom et al., 2009, Carpenter et al., 2015, 2017, Mathias et al., 2017) for governing functions as individuals, and common safe operating spaces for the forest multi-functionality. Such an approach can bring new insights to the management and development of social-ecological systems encompassing a concept of multi-functionality.

ACKNOWLEDGMENTS

This research has been funded by the ANR (Agence Nationale de la Recherche) under the VIRGO project (ANR-16-CE03-0003) and the region of Auvergne. Moreover, this research was conducted on the Long-Term Socio-Ecosystem Research platform LTSER "Zone Atelier Alpes", a member of the ILTER-Europe network.

REFERENCES

At the end of the manuscript

[Earth's Future]

Supporting Information for

[An infrastructure perspective for enhancing multi-functionality of forests: A conceptual modeling approach]

[M.HOUBALLAH[1], JD MATHIAS[1], T.CORDONNIER[2]]

[[1] Université Clermont Auvergne, Irstea, UR LISC, Centre de Clermont-Ferrand, 9 avenue Blaise Pascal CS 20085, F-63178 Aubière, France. [2] Université Grenoble Alpes, IRSTEA, UR LESSEM, 38000 Grenoble, France.]

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Additional Supporting Information (Files uploaded separately)

Captions for Tables S1 to S1: Definitions, references, dimensions, and values of parameters found in the model.

Introduction

In this document, we present an analysis of the model at equilibrium points. In particular, we are interested in the behavior of forest functions and their tradeoffs at equilibrium points.

Equilibrium points:

In this document, we focus on the so-called "sustainable solution", i.e., when the coupled infrastructure structure is sustained in the long run. Setting the left-hand side of Eq. (1) to zero and using * to denote the long term equilibrium, we are interested in properties of the following equilibrium points:

$$x_1{}^* = \frac{hx_2{}^* v_1 - h_m H^F(S_I{}^*, C_I{}^*)}{v_1(g_1 uhx_2{}^* + d)} \tag{2}$$

$$x_2{}^* = \frac{sbg_1^2 x_1{}^{*2} - bg_1 x_1{}^*}{ug_1 hx - sbg_1 x_1 g_2 - h - zg_1 x_1{}^* - d} \tag{3}$$

$$V_d{}^* = \frac{\begin{array}{c} v_2 x_2{}^*(zg_1 x_1{}^* + d) + (h_m \times H^F(S_I{}^*, C_I{}^*))(1 - p_e) \\ -(o \times v_1 x_1{}^* dp_e p_a \times H^F(S_I{}^*, C_I{}^*)) \\ +v_1 x_1{}^* d \end{array}}{\alpha} \tag{4}$$

$$T^* = \frac{E({x_1}^*, {x_2}^*) + H^T({S_I}^*, {C_I}^*) - a}{\alpha_T} \tag{5}$$

$${S_I}^*\left(M(1 - {S_I}^*) - \frac{\varepsilon}{{C_I}^*} - \delta\right) - \frac{\varepsilon S_{I_m}}{{C_I}^*} = 0 \tag{6}$$

$$(\alpha_2 \times I_{BA} \times B_A \times u_2 \times \mu) \times {C_I}^* \times \left(1 - \frac{{C_I}^*}{C_{Imax}}\right) = 0 \tag{7}$$

Where all parameters of the coupled dynamics are defined in the table (S1).

Accordingly, functions H^F and H^T are expressed as follow:

$$H^F({S_I}^*, {C_I}^*) = \begin{cases} 0, & {S_I}^* < S_{I_0} \\ {C_I}^* \dfrac{{S_I}^* - S_{I_0}}{S_{I_m} - S_{I_0}}, & S_{I_0} \le {S_I}^* \le S_{I_m}, \\ {C_I}^*, & {S_I}^* > S_{I_m} \end{cases} \tag{8}$$

$$H^T({S_I}^*, {C_I}^*) = \begin{cases} 0, & {S_I}^* < S_{I_{0T}} \\ a_T e^{-\frac{({C_I}^* - C_{I_{0T}})}{2c_T^2}} \dfrac{{S_I}^* - S_{I_{0T}}}{S_{I_{mT}} - S_{I_{0T}}}, & S_{I_{0T}} \le {S_I}^* \le S_{I_{mT}} \\ a_T e^{-\frac{({C_I}^* - C_{I_{0T}})}{2c_T^2}}, & {S_I}^* > S_{I_{mT}} \end{cases} \tag{9}$$

From Eq. (7), we have:

$${C_I}^* = 0 \text{ or } {C_I}^* = C_{Imax} \text{ or } (\alpha_2 \times I_{BA} \times B_A \times u_2 \times \mu) = 0 \tag{}$$

However, we suppose that **roads initial condition is different from zero** and cannot be deteriorated to the point where it completely disappears. Therefore, we have ${C_I}^* \neq 0$. Moreover, we are interested in the idea that the forest reaches a sustainable outcome at the same time while being managed by the government. Therefore, we have $(\alpha_2 \times B_A \times u_2) \neq 0$. As a consequence, a sustainable outcome is found at ${C_I}^* = C_{Imax}$. Assuming that

Assuming that $C_{Imax} = 1$ and substituting ${C_I}^* = C_{Imax} = 1$ in Eq. (6), we have:

$${S_I}^* = 1 - \frac{\delta(1+k)}{\alpha_2 I_{BA} B_A u_2}$$

And the above equations [Eq. (8), (9)] lead to the following identities:

$$H^F({S_I}^*, {C_I}^*) = \frac{1 - \dfrac{\delta(1+k)}{\alpha I_{BA} B_A u_2} - S_{I_0}}{S_{I_m} - S_{I_0}} \tag{10}$$

and

$$H^T({S_I}^*, {C_I}^*) = a_T e^{-\frac{(1 - C_{I_{0T}})}{2c_T^2}} \frac{1 - \dfrac{\delta(1+k)}{\alpha I_{BA} B_A u_2} - S_{I_{0T}}}{S_{I_{mT}} - S_{I_{0T}}}$$

Fig. S1 illustrates the two functions found in Eq. 10 on both sides at equilibrium states (${C_I}^* = 1$), with different values of B_A for the right-hand side equation (RHS).

In addition to illustrating Eq. 10, Fig. S1 highlights the effect of the budget on the equilibrium state of H^F. Meaning:

- To have a high value for a sustainable state for H^F, you have to have a high budget, and the higher that value of H^F, the high budget that you need
- For the roads to be at full capacity, the budget (BA) must be at least $\frac{\delta(1+k)}{(S_{I_m}-S_{I_0})\alpha_2 I_{BA} u_2}$. Substituting values for parameter, we get BA should be 506 at equilibrium state to reach a full capacity infrastructures state

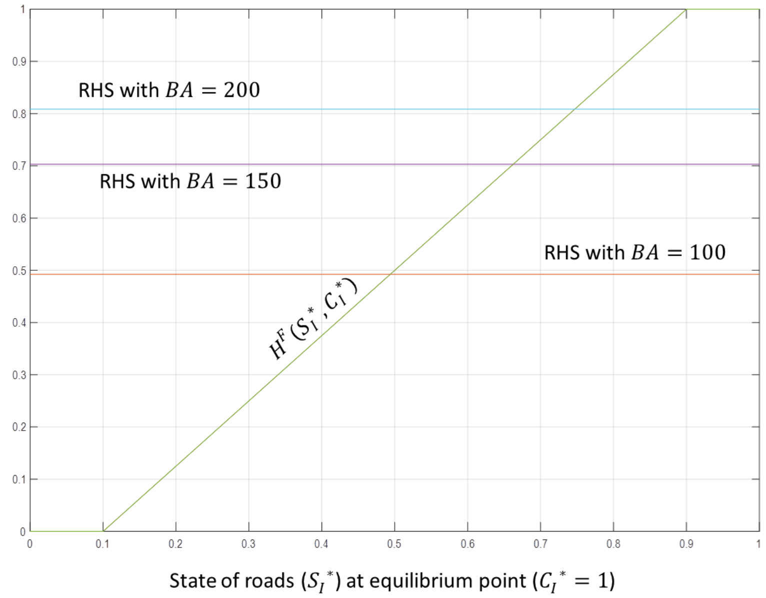

Figure S1. Illustration of the solution to Eq. 10 on both sides

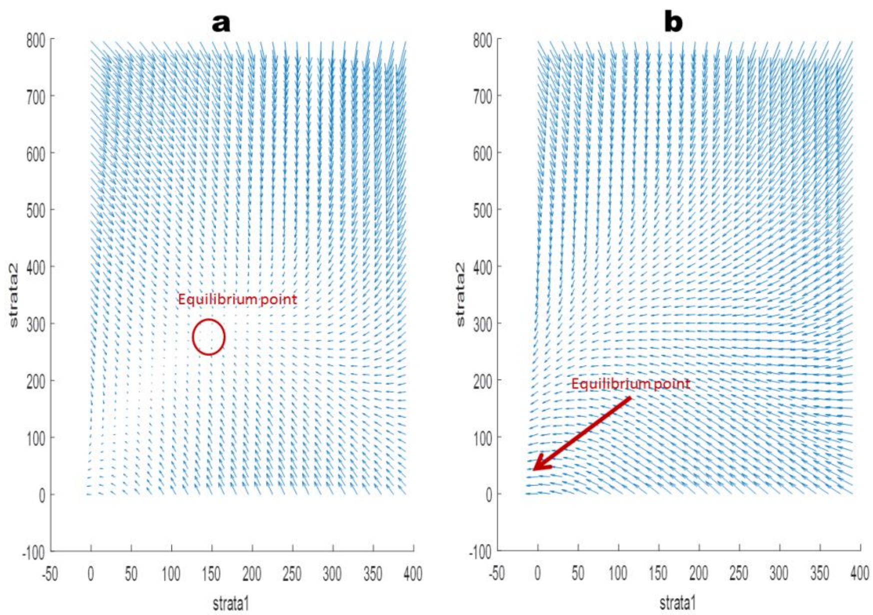

Figure S2. 2d-Quiver plot of stratum 1 (big trees) and stratum 2 (small trees) at equilibrium state with BA=200. Panel (a) represents equilibrium points with h_m=10; panel (b) represents equilibrium points with h_m=30 where it moves towards zero.

Moreover, Fig. S2 illustrates the position of equilibrium points according to two values of wood removal (10 m^3/ha and 30 m^3/ha). It shows that the equilibrium point moves toward zero whenever we have a high extraction of wood, presenting a clear case of over harvest, and cascading failure of forest functions

Table S1. Definitions, references, dimensions, and values of parameters found in the model.

Parameters

Symbols	Reference	Definition	Unit	Range/value
$\boldsymbol{H^F}$	Muneepeerakul and Anderies 2017	Infrastructure enhancement function	C_I	$[0-1]$
$\boldsymbol{H^T}$	Muneepeerakul and Anderies 2017	Infrastructure attractiveness function	$\left[\frac{1}{t}\right]$	$[0-1]$
$\boldsymbol{h_m}$		Wood removal objective	$\left[\frac{m^3}{C_I}\right]$	10
$\boldsymbol{\delta}$		Depreciation rate of infrastructure	$\left[\frac{1}{S_I}\right]$	0.05
$\boldsymbol{S_{I_0}}$		Threshold of S_I below which H^F is zero	$[S_I]$	0.1
$\boldsymbol{S_{I_m}}$		Threshold of S_I above which H^F is maximum relative to C_I	$[S_I]$	0.9
$\boldsymbol{S_{I_{0T}}}$		Threshold of S_I below which H^T is zero	$[S_I]$	0.01
$\boldsymbol{S_{I_{mT}}}$		Threshold of S_I above which H^T is maximum relative to C_I	$[S_I]$	0.4
$\boldsymbol{b}$	Mathias et al. 2015	Intrinsic recruitment rate	$NbInd\ m^{-2}\ ha\ t^{-1}$	0.75
$\boldsymbol{s}$	Mathias et al. 2015	Recruitment sensitivity to light interception	$ha\ m^{-2}$	0.0125
$\boldsymbol{u}$	Mathias et al. 2015	asymmetric competition with stratum 1	$ha\ m^{-2}$	0.0167
$\boldsymbol{h}$	Mathias et al. 2015	Growth rate from stratum 2 to stratum 1	t^{-1}	0.025

$g_1(d_1, h_1, v_1)$	Mathias et al. 2015	Basal area of stratum 1		0.16 (0.45,25,2.29)
$g_2(d_2, h_2, v_2)$	Mathias et al. 2015	Basal area of stratum 2		0.013 (0.0125,7,0.066)
z	Mathias et al. 2015	Mortality process in stratum 2 due to asymmetric competition	$t^{-1}\, ha\, m^{-2}$	0.0008
d	Mathias et al. 2015	Intrinsic mortality in strata 1 and 2	t^{-1}	0.0067
T_{c_F}	none	Tax contribution of wood removal users to the government	$[-]$	$[0.1 - 0.4]$
T_{c_T}	none	Tax contribution of tourism users to the government	$[-]$	$[0.1 - 0.2]$
p	Memoire Bachard 2011	Price of $1\, m^3$ of timber	[$]	50
c_m	Memoire Bachard 2011	Cost of extracting $1\, m^3$ of timber	[$]	21
α	Mathias et al. 2015	Rate of decay of deadwood	$[-]$	0.06
p_e	Mathias et al. 2015	Ratio of timber volume effectively exported	$[-]$	0.9
p_a	Mathias et al. 2015	Ratio of deadwood removed for commercial purposes	$[-]$	0.9
α_1		Ratio of the budget targeted at construction of roads	$[-]$	$[0 - 1]$
u_1	Muneepeerakul and Anderies 2017	The effectiveness of investment in the construction of roads	$\left[\frac{C_I}{\$}\right]$	4
μ		The growth per unit of road	$\left[\frac{1}{C_I}\right]$	0.0005
α_2		Ratio of the budget targeted at maintenance of	$[-]$	$[0 - 1]$

		roads		
u_2	none	The effectiveness of investment in the maintenance of roads	$\left[\frac{S_I}{\$}\right]$	0.2
$C_{I^{max}}$	none	Maximum value for roads on the forest	$[C_I]$	1
a	Casagrandi and Rinaldi 2002	Expected attractiveness of the forest	$[-]$	0.1
α_T	Casagrandi and Rinaldi 2002	Ratio of congestion of tourists	$[-]$	9×10^{-5}
a_T	none	The maximum attractiveness related to the road availability	$[-]$	1
C_{I_0}	none	The number of roads in which the perception of tourists is considered the highest	$[-]$	0.5
c_T	none	The rate of increase/decrease in attractiveness when increasing the number of roads	$[-]$	1
o	none	Ratio of deadwood removal per one road unit	$\left[\frac{1}{C_I}\right]$	1
p_d	Memoire Bachard 2011	Price of $1\,m^3$ of deadwood	$[\$]$	40
c_d	Memoire Bachard 2011	Cost of extracting $1\,m^3$ of deadwood	$[\$]$	21
π_T		Revenue ratio collected from the tourists	$\left[\frac{\$}{T(t) \times t}\right]$	1
B_A		Annual budget calculated from the taxes of functions	$\left[\frac{\$}{t}\right]$	$\sim[0 - 1000]$
I_{BA}		Ratio of the	$[-]$	0.5

		budget for provisioning of roads		
$\boldsymbol{k}$		The rate of decrease in road maintenance effectiveness	$[C_I]$	80
$\boldsymbol{\varepsilon}$		The number of roads introduced at time t.	$\left[\frac{C_I}{t}\right]$	$[0-1]$
$\boldsymbol{x_1^0, x_2^0}$		the assumed most attractive forest structure for tourists	$\left[\frac{x_1}{ha}\right], \left[\frac{x_2}{ha}\right]$	$200, 400$
$\boldsymbol{\omega_1, \omega_2, \omega_3}$		the rate of change of the forest attractiveness	$\left[\frac{1}{x_1}\right], \left[\frac{1}{x_1 x_2}\right], \left[\frac{1}{x_2}\right]$	15×10^{-4}, -7×10^{-5}, 9.9×10^{-5}

Chapter 4

Adaptive management and forest policies

4.1 A viability analysis of adaptive managements

The dynamical model developed in the previous chapter has been analyzed thoroughly to present the role of infrastructures to mediate the interactions between forest functions. As mentioned in **Chapter 3**, infrastructure effect is modeled through the "infrastructure enhancement functions", which adopts the non-linear behavior of such entities. However, through this chapter, we seek to tackle the problem of adaptive management and safe operating spaces with an inaugurated role of infrastructures. The work presented here endorses the viability theory to study adaptive and viable policies for maintaining the forest's dynamical system within the defined safe operating space at the multi-functional level. However, due to the complexity of the model presented in **Chapter 3** that imposes an 8D viability problem, we limit our analysis to an embedded 3D problem that deals with the interplay between two forest functions (tourism and wood removal).

This chapter starts with an introduction of the dynamical model used for the viability problem. This inspired model deals with connecting two forest functions through infrastructures. The study deals with analyzing the direct effect of infrastructures on tourism and timber removal, and as a result, we consider the environmental aspect of the forest to be fixed. In particular, we are interested in the infrastructure provision policies that enable the multi-functionality of the forest and improve its performance. For the sake of simplicity, the viability problem is first applied in a context referring only to tourism as a function. Consequently, because of the assumptions that deal with infrastructures as a driver for extracting trees, we introduce wood removal function as a constraint on infrastructures state and quantity (a minimum state and set of roads are needed in order for the forest function to be operational). We explore the implication of two infrastructure policy provision approaches; one which halts all road construction if needed, and one which doesn't. The article finishes with a brief interpretation of the preliminary result obtained.

4.2 Presentation and contribution of the article

This article is still an ongoing work. It is intended as a preliminary result for a viability characterization of adaptive management and safe operating spaces. Here, we present a simple a simple viability approach (3D viability problem) that deals with our problem of multi-functionality. The principal contributions of this article are the following:

- Define adaptive management of the forest function through infrastructures provision policies (governance control)

- Describe the behavior of SOSs according to the interplay between tourism and wood removal functions

- Analyze the effect of infrastructures according to provisioning strategy that completely halts road construction if the context permits, and to one which does not

4.3 Conclusions

Although the problem of forest multi-functionality addressed here considers only two functions in the forest, the trade-offs identified between these functions have been highlighted by the significant change in safe operating spaces. Therefore, this calls for a need to develop strategies that are able to consolidate, through infrastructure provision strategies, the difference between the corresponding safe operating space for tourism and wood removal function, respectively. We have tested two approaches for infrastructure provision: a strategy that completely halts road construction if the context permits, and one which does not , and however, found that in forests, the impact of maintaining a relatively appropriate set of infrastructures in a high infrastructure abundance context offers a more sustainable and resilient approach than that of building. This offers an insightful view on adaptive management strategies in forestry. However, there is a need for a far more sharp viability analysis that takes into account the dimensionality and the dynamics of forest structure and biodiversity respectively.

4.4 Text of the article

Original Manuscript

Title [ADAPTIVE MANAGEMENT OF INFRASTRUCTURES TO OPERATIONALIZE MULTIFUNCTIONAL SAFE OPERATING SPACE FOR FORESTS]

[Mojtaba HOUBALLAH[1], Jean – Denis MATHIAS[1], Thomas CORDONNIER[2]]

[1] Université Clermont Auvergne, Irstea, UR LISC, Centre de Clermont-Ferrand, 9 avenue Blaise Pascal CS 20085, F-63178 Aubière, France

[2] Université Grenoble alpes, IRSTEA, UR LESSEM, 38000 Grenoble, France.

Corresponding author: Mojtaba Houballah (mojtaba.houballah@gmail.com)

Abstract

The usefulness of forests is spread from their exploitation for timber, tourism, and other functions to maintenance of wildlife, ecological balance, and prevention of soil erosion. In achieving these goals, the essential factor is proper forest management. However, with the increasingly perceived idea that forests are characterized by complex interactions related to biological and social aspects, forest management is facing a challenge, which consists in integrating interrelations between ecological and social systems. While sustainable forest management is originally seen as a constant yield of wood supply, modern ideas of sustainability are broader in scope, embracing all goods and services of the forest. Increasingly, forests are being managed as multi-functional ecosystems. In this vein, forests are progressively seen as complex social-ecological systems (SESs), requiring adaptive and multi-functional management. In this Ph.D. thesis, we consider that the question of management application can be tackled by understanding how shared infrastructures mediate the interaction between human and ecological environment. In particular, for sustainable and multi-functional forest management, the relation between the capacity for production as well as multi-functional use is highlighted with the concept of forest's shared infrastructures that are mainly composed of roads (accessibility utilities). However, dilemmas associated with their provision pose some problems when it is applied in a context of different forest functions with conflicting objectives. Therefore, to fully understand and integrate the role of infrastructure and their governance into ecosystem science, we base our research on three parts. We use viability theory on an inspired forest model that takes into account the infrastructure provision function dynamically. Obtaining the viability kernels, we distinguish between different scenarios of tourism-oriented and multi-functionality oriented forest management. We observe the effect of two different infrastructure provision policy approaches that favor constructing or maintaining roads to avoid the non-viability of the system.

Keywords: Social-ecological system; robustness framework; forest governance; forest functions; infrastructures;

1. Introduction

Many of the world's forests and woodlands are still not managed sustainably. Some countries lack appropriate forest policies, legislation, institutional frameworks and incentives to promote sustainable forest management, while others may have inadequate funding and lack of technical capacity. Where forest management plans exist, they are sometimes limited to ensuring the sustained production of wood, without paying attention to the many other products and services that forests offer [Forest resource assessment 2015]. Sustainable forest management can be defined as the use of forest resources in a way and at a rate that maintains their biodiversity, productivity, regeneration capacity, and their potential to fulfill now, and in the future the relevant ecological economic and social functions [Martin-Garcia and Diez 2012]. It has originally been seen as a constant yield of wood supply but now is broader in scope, embracing all goods and services of the forest. As a result, progressively, forests are being managed as multifunctional ecosystems [Farrell et al. 2000].

Forest multifunctional management, which also highlights the ecological and economic roles of forest ecosystems for society, has become a central objective for several European countries (e.g., France, Italy, and Germany) [Slee 2012]. In this vein, such practice is defined as a land-use strategy capable of meeting divergent societal interests, supporting forestry practices adaptable to different social groups, and remaining consistent with the principles of sustainable development [Schmithüsen 2008].

The relation between multifunctional forest use as well as the capacity for forest production is highlighted with the concept of infrastructures [Bizikova et al. 2012, Yu et al. 2015]. Understanding how such infrastructures mediate the interaction between human functions in the natural environment helps confront questions of management application and consequently improve forest sustainability. In view of this, infrastructures are broadly defined to include natural and human-made infrastructures (both physical and social) that enable the operation of society. However, infrastructure design must comply with the principles of sustainable development. This requires, amongst other things, that this design must play a role in helping forests maintain their structure and ecosystem functioning despite disturbances (i.e., climate change) [Bebbington et al. 2018]. Therefore, a development, through infrastructure provision, of adaptive multifunctional forest management application in the face of shocks is a key challenge for future resource management in Europe and worldwide [Bolte et al. 2009].

The concept of sustainability is difficult to operationalize in any meaningful sense in an SES governance context for a range of reasons [Anderies et al. 2013, Benton et al. 2018]. In principle, however, the concept of "safe operating space" (SOS; Rockstrom et al. [2009], Carpenter et al. [2015, 2017]) is perhaps intrinsically more straightforward in a real-world context, through defining boundaries. Nevertheless, to make the concept operational in an SES, we then need to have a concrete methodological framework to translate it into a set of government policies that will maintain the system within its operational boundaries. In the face of the well-known problem of "operationalizing sustainability", the concept of SOS can be based on the widespread agreement that sustainability implies the existence of limits, thresholds, tipping points or constraints on the natural world as well as the socio-economic functional system. In this vein, sustainability is about maintaining the system within these constraints and boundaries.

One practical solution for maintaining SOSs relies on adaptive management that enables decision-makers to balance needs and constraints in a dynamical way based on the state of exploited forests. In particular, adaptive management [Holling 1978] is often put forward as a more realistic and promising approach to deal with forest's ecosystem complexity [Gunderson 1999] than management for optimal use and control of the resources [Holling and Meffe 1996, Ludwig and Haddad 2001]. In this vein, such concepts of SOSs and adaptive management are straight-forward to grasp by policymakers.

In this article, we aim to use viability theory [Aubin 1991] as a tool to operationalize sustainability in forests by linking the concepts of sustainability, multi-functionality, SOSs, and adaptive management. Based on a previous study [Houballah et al. 2019] that developed an approach to connect forest multi-functionality to infrastructures' multi-functionality, we use an inspired mathematical model that highlights infrastructure roles in the performance of forest functions. This model takes into account tourism as a main function in the forest. We study the influence of infrastructures and their provision strategies on SOSs defined by constraints on tourism, nature conservation, as well as wood extraction functions. In particular, we study governance strategies and their impact on SOSs. Our aim here is to contribute to building a theoretical foundation to understand how infrastructures can influence the performance of functions and eventually the sustainability of the forest.

2. Materials and Methods

2.1 Model

As mentioned before, we base our analysis construction on an inspired model from Houballah et al. [2019] to analyze the interaction of governance with the forest through infrastructures. The model deals with forest functions being affected by both the environment of the forest and the capital needed to function. However, in this article, we are interested in the performance of the tourism function and therefore focus on its dynamics regarding the capital. For an overall identification of parameters and their values used in the model, see table (S1) in the appendix.

2.1.1 Capital governance in the forest

The analysis focuses on understanding the nature of economic and political governance from an infrastructural point of view. In this context, governance in the forest is highlighted by the ability to provide public shared infrastructure. Their behavior is manifested in the amount of resources collected from tourism that is appropriated by the governance for maintaining and constructing roads in the forest. The annual budget (B_A) of the governance is composed of taxes (T_{c_T}) paid by tourism users, as well as subsidies (γ), paid either by the French government or the European Union for forest management in the Western Alps, and is given by the following equation:

$$\boldsymbol{B_A(t)} = \left(\overbrace{\boldsymbol{hm \times H^F(S_I(t), C_I(t)) \times (p - c_m)}}^{\textit{revenue of timber harvest}}\right) \times \overbrace{\boldsymbol{T_{c_F}}}^{\textit{forestry tax contribution ratio}} + \left(\overbrace{\boldsymbol{\pi_T T(t)}}^{\textit{revenue from toursim function}}\right) \times \overbrace{\boldsymbol{T_{c_T}}}^{\textit{tourism tax contribution ratio}} + \overbrace{\boldsymbol{\gamma}}^{\textit{subsidies}}$$

The model considers that roads in the forest are multi-functional and are used for all forest functions. On one hand, governance in the forest can decide to introduce new roads as a part of a strategy for increasing accessibility in the forest; this decision is based upon its measured effectiveness as well as the amount of money allocated for that purpose. In order to define a system of road network development, we first consider (1) the idea that existing roads trigger the development of more roads and (2) the forest, being a finite space, can only withstand a maximum number of road units. Therefore, the dynamics of the number of road unit measured in [C_I] unit in the forest can be expressed by the following logistic growth equation:

$$\boldsymbol{\frac{dC_I(t)}{dt}} = \overbrace{\boldsymbol{(\alpha_1 \times I_{BA} \times B_A(t) \times u_1 \times \mu)}}^{\textit{Growth}} \times \boldsymbol{C_I(t)} \times (\boldsymbol{1} - \boldsymbol{\frac{C_I(t)}{C_{Imax}}}),$$

On the other hand, governance is responsible for maintaining the road infrastructure in the forest, the behavior of such action is mediated by the amount of money allocated from the annual budget of the governance as well as the effectiveness of such action. Moreover, maintenance is reduced by the increasing number of road units as the effectiveness of the maintenance budget becomes less efficient. The function of maintenance can be expressed by the following equation:

$$\boldsymbol{M(t)} = \boldsymbol{\alpha_2 \times I_{BA} \times B_A(t)} \times (\overbrace{\boldsymbol{u_2} \times \boldsymbol{\frac{1}{C_I(t) + k}}}^{\textit{effetiveness decreased by the increased } C_I(t)})$$

Maintenance of infrastructure is seen as a logistic growth of a road state dynamic. In particular, at low state the growth is considered little due to the poor conditions of roads (using roads to maintain other roads), however, the growth increases with the increase of the state until it reaches very high quality and becomes costly to maintain. Moreover, introducing a new road has a positive effect on the state dynamics, where the newly built roads are considered to have maximum quality, and however, negatively affected by the depreciation effect. The dynamics of the state of roads $S_I(t)$ is described as follows:

$$\frac{dS_I(t)}{dt} = \overbrace{M(t) \times S_I(t) \times (1 - S_I(t))}^{maintenance} + \underbrace{\frac{\varepsilon(S_{I_m} - S_I(t))}{C_I(t)}}_{effect\ of\ introducing\ a\ new\ road} - \overbrace{\delta S_I(\mathbf{t})}^{depreciation}$$

2.1.2 Forest functions

Tourism function

The dynamical model for tourism represents the "outside social demand" in the forest and we consider that tourism, as a forest function, is measured according to the number of tourists the forest can attract. Assumptions on the model include interactions between three important components of the coupled system: the tourists, environment, and infrastructures [Casagrandi and Rinaldi 2002, Houballah et al. 2019]. The dynamics of the model is as follows:

$$\frac{dT}{dt} = T[\overbrace{E}^{attractivenss\ of\ the\ environement} + \overbrace{H^T(S_I, C_I)}^{attractiveness\ of\ the\ infra.} - \overbrace{\alpha_T T}^{congestion} - \overbrace{a}^{expected\ attractivenss}]$$

- E represents a function that measures the attractiveness of the natural environment (regarding its tree structure). In this work, we consider the forest is composed of two strata, big tree stratum (x_1) and small tree stratum (x_2). The environmental attractiveness can take values with respect to a fixed structure according to E, which is expressed as a 2-d Gaussian-like function:

$$f(x_1, x_2) = exp\left(-(\omega_1(x_1 - x_1^0)^2 + 2\omega_2(x_1 - x_1^0)(x_2 - x_2^0) + \omega_3(x_2 - x_2^0)^2)\right)$$

- $H^T(S_I, C_I)$ represents the attractiveness of roads associated with their state $S_I(t)$ and quantity $C_I(t)$. The behavior of attractiveness considers that for a certain amount of roads the perception of tourists is considered to be the highest, after this value the perception starts declining due to the "congestion of infrastructure". The function that considers such behavior can be expressed as a piecewise Gaussian-like function:

$$H^T(S_I, C_I) = \begin{cases} 0, & S_I < S_{I_{0T}} \\ a_T e^{-\frac{(C_I - C_{I_{0T}})^2}{2c_T^2}} \dfrac{S_I - S_{I_{0T}}}{S_{I_{mT}} - S_{I_{0T}}}, & S_{I_{0T}} \le S_I \le S_{I_{mT}} \\ a_T e^{-\frac{(C_I - C_{I_{0T}})^2}{2c_T^2}}, & S_I > S_{I_{mT}} \end{cases}$$

All parameters are expressed in table (1) with clear definitions, references, and values.

Wood extraction function

In order to favor timber production, a key issue is the mobilization of timber stocks from the forest to its corresponding industries. Thus, the wood extraction function is considered to be enhanced by infrastructures in the forest due to the facilitated accessibility it offers. The model considers that the road functionality exhibits a non-linear behavior; once the state of forest roads become so poor that it falls below a certain threshold, one that is related to major road blockage, the road's employment in accessibility stops working. Moreover, the productivity of users is linked as well to the availability of infrastructure. The behavior of road's enhancement is represented by a piecewise function:

$$H^F(S_I(t), C_I(t)) = \begin{cases} 0, & S_I(t) < S_{I_0} \\ C_I(t)\,\dfrac{S_I(t) - S_{I_0}}{S_{I_m} - S_{I_0}}, & S_{I_0} \le S_I(t) \le S_{I_m}, \\ C_I(t), & S_I(t) > S_{I_m} \end{cases}$$

2.2 Viability Theory to characterize safe operating spaces

In its context, the viability theory [Aubin 1991] can be used to answer questions to determine sustainable policies for decision-makers. From a general view, the theory has been explicitly developed for the purpose of analyzing dynamical systems that face constraints, making it a perfect fit for considering problems of analyzing adaptive management and maintaining some dynamical system in its defined SOS. As discussed in Krawczyk and Pharo [2013], viability theory will be compelling to those wishing to acquire information about the sustainability of dynamical systems they are studying: (1) can the system maintain itself according to a given sustainability criteria? (2) what are the necessary conditions for sustainability (3) which initial system states allow the possibility of the system to maintain itself inside some defined SOS, and which do not? Furthermore, where systems are susceptible to control by a government, viability theory is also appealing to those wishing to determine rules and governance/management strategies that help in attaining adaptive management: (3) what strategies can be pursued to ensure and improve the sustainability of the system? and (4) what other strategies are compatible with the sustainability of the system.

For that, to tackle our problem of sustainability regarding multifunctional forests and the role infrastructures and their provision, we consider viability theory to be a relevant approach. For a detailed explanation of the mathematical formulation of viability theory, see appendix S1.

2.2.1 Specifying the control

As the model's rationale takes into account infrastructure's influence on the forest and its functions, we consider that governance can affect this influence by introducing an infrastructure provision strategy that is confined in two controls:

- Maintenance/construction control: we consider that the annual budget directed towards infrastructure provision can either be directed towards maintenance of roads or construction of roads. This strategy is represented by the ratio function $\alpha_1(t)$ in which it allocates α_r towards the construction of roads, in which it automatically allocates $1 - \alpha_1(t)$ to maintenance. The function $\alpha_1(t)$ given as follows:

$$\boldsymbol{\alpha_1(t) = \alpha_r \ such\ that\ \alpha_r \in [0, 0.7]}$$

- Tax imposition control: we consider that annual taxes are imposed on the forest functions economic performance and with an imposition function on wood extraction ($T_{C_F}(t)$) and that of tourism ($T_{C_T}(t)$). The taxation strategy in this model is considered to be linked for both functions, and thus are subject to a scaled increase/decrease. The function is given as follows

$$\boldsymbol{T_{C_F}(t) = T_F \ such\ that\ T_F \in [0, 0.3]},$$

$$\boldsymbol{T_{C_T}(t) = \frac{T_{C_F}}{2}}$$

2.2.2 Specifying socio-economic constraints

We consider two socio-economic constraints: one which is related to tourism functionality and the other is related to wood extraction in the forest.

First, tourism function dictates that the forest has to have a minimum number for tourists to be considered functional in the forest. Thus, the constraint is represented as follows:

$$\boldsymbol{T^{min} < T(t), \forall t} \tag{1}$$

Embedded in this constraint, there is an understanding that the structure of the forest has to be maintained in order to be able to keep this minimum number of tourists. Therefore, form a subjective point of view, this constraint also considers the maintenance of the environmental aspect of the forest.

Here we focus on the infrastructure role in enabling the performance of functions. Therefore we consider having a constraint on infrastructures to the point that allows the wood extraction to be viable with the wood extraction function objectives. The constraint is outlined as follows:

$$\boldsymbol{I_r^{min} < C_I(t)\frac{S_I(t) - S_{I_0}}{S_{I_m} - S_{I_0}}, \forall t} \tag{2}$$

Considering the multi-functionality of roads in our model's context, we consider that the adopted constraint also considered being a constraint on the performance of tourism.

2.2.3 Designing scenarios

As mentioned earlier, we consider an embedded 3D viability problem, in which we define two stylized scenarios:

- An SOS for tourism performance (reference scenario): for the sake of simplicity, we consider a constraint the deals only with the performance of tourism
- An SOS to determine multi-functionality (multifunctional scenario): as it is the essence of the model's rationale, we consider that the outcomes of the functionality of the forest can be influenced by several socio-economic constraints related to two forest functions (Tourism and wood extraction). Therefore, we study the behavior of the SOS according to constraints that deals with the performance of these two functions

3. Results

In this work, the viability kernel is computed according to an algorithm inspired by Saint-Pierre [1994]. An Euler integration scheme with a one-year time step was used for time discretization. Recall that for instantaneous control, according to the semi-permeability of the viability kernel, there is at least a single control viable for any point on the border of the viability kernel, and all controls are viable for all other points of the viability kernel. For every kernel computation, we used a minimum discretization grid of 100 points per dimension for the state space.

As mentioned before, we consider parameter values given in table (S1) found in the appendix. We consider 3d views of the viability kernel with different values of infrastructure (S_I and C_I), tourism (T), and for different fixed forest structures (x_1 and x_2). However, with the following simulation, we adopt the infrastructure provision strategy that favors building roads to maintaining existing ones. We recall that the viability kernel is the zone from which there is at least a policy that complies with the socio-economic constraint outlined earlier.

3.1 Reference scenario

For the sake of simplicity, we first consider only a constraint for the functionality of tourism. Meaning, we take into account socio-economic constraint that deals only with tourism. Thus, we consider the constraint in eq. (1) with $T^{min} = 6 \times 10^3$. Figure 1 represents the viability kernel corresponding to the endorsed problem.

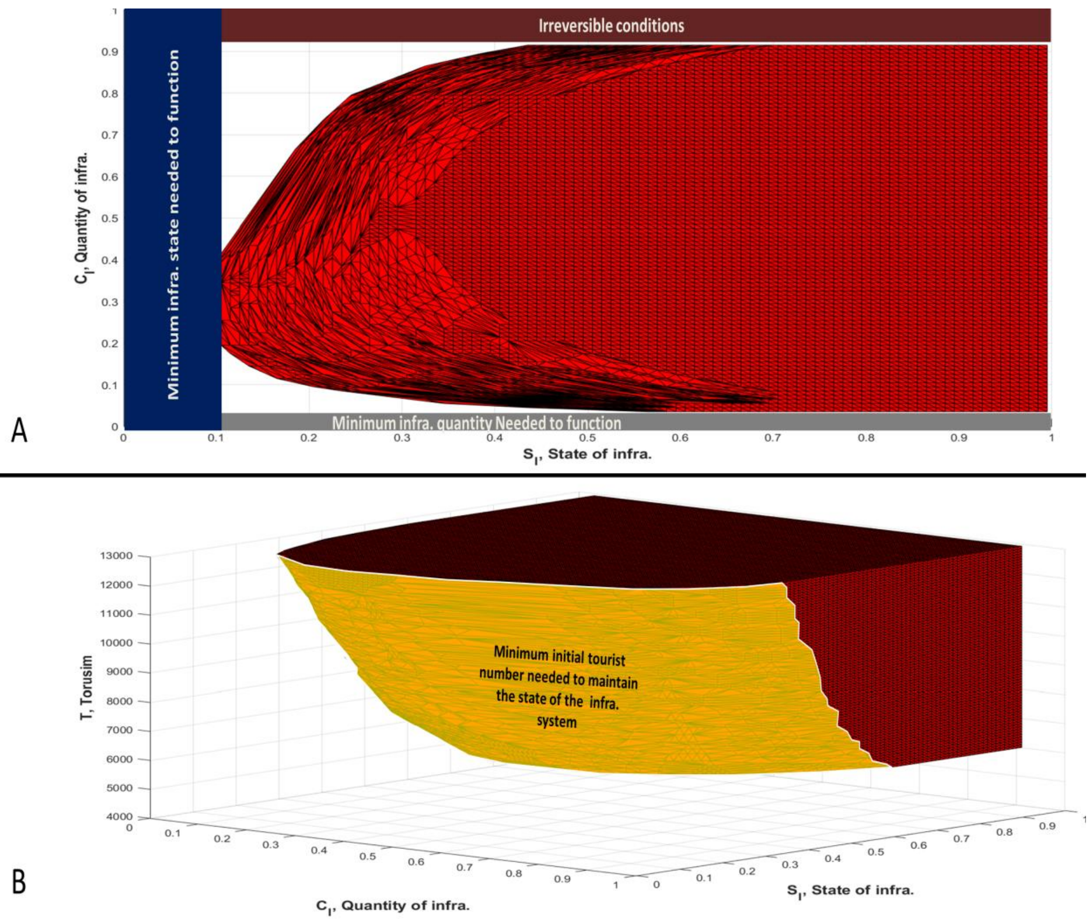

Figure 1. Viability kernel of the adopted problem with a reference scenario. The red area corresponds to viable states for the tourism function. Panel A represents a 2D view of the viability kernel, whereas panel B corresponds to the respective 3D view of the set. Monitoring the system within the constraint set represents a trade-off between the quantity/quality of infrastructures and the initial number of tourists

When the state of infrastructure is very low (low S_I value), the system is non-viable because of the minimum requirement for the state to ensure the attractiveness of the infrastructure (see blue area in Fig. 1, panel A). Indeed, due to the non-linear nature of infrastructures context adopted, low roads' state compels the perception of tourists to view the forest as unappealing. This results in a lower tourist attraction, one which is lower than the threshold of functionality (see eq. 1) for tourism.

On one hand, Fig. 1 shows that for a small number of infrastructures, the system is not viable because of the minimum required set of roads needed in order for tourism to function (see grey area in Fig. 1, panel A). Naturally, the initial number of tourists in the forest is not sufficient in order to produce money for building roads and surpassing the minimum threshold for infrastructure attractiveness regarding the number of roads, which normally will lead to crossing the constraint of the functionality of tourism.

On the other hand, because of the nature of the attractiveness of infrastructure function adopted in this model, having too many roads will lead to non-viable states for tourism (see brown area in Fig. 1, panel A). Indeed, crossing this threshold is regarded as a tipping point, in which there is no governance policy or strategy to lower the number of roads that will lead eventually to a deteriorated performance of the function.

Moreover, Fig 1, panel B shows that for a mediated infrastructure state (approximately $0.05 < S_I < 0.9$), the system is non-viable (yellow markings). Certainly, to maintain the attractiveness with balanced values between the quality and quantity of infrastructures, there is a need for a budget that is able to enforce it. Thus, initial tourist numbers are essential to maintain the budget needed for the infrastructures and eventually, ensure the viability of the system.

3.2 Multi-functionality scenario

As mentioned before, achieving increased and desirable outcomes for both wood extraction and tourist numbers requires improvements in forest system infrastructure management. For this purpose, we consider a 3D viability problem with a fixed forest structure. Meaning that we fix x_1 and x_2 and compute the viability kernel according to the dynamics of C_I, S_I, and T. The socio-economic constraints for this problem deal with the multi-functionality problem, and are given as follows:

- Constraint on tourism (see eq. 1), which ensures the performance of the function; with $T^{min} = 6 \times 10^3$;
- Constraint on the infrastructure states (see eq. 2), which defines a basis for their employment in wood extraction activities; with $I_r^{min} = 0.3$;

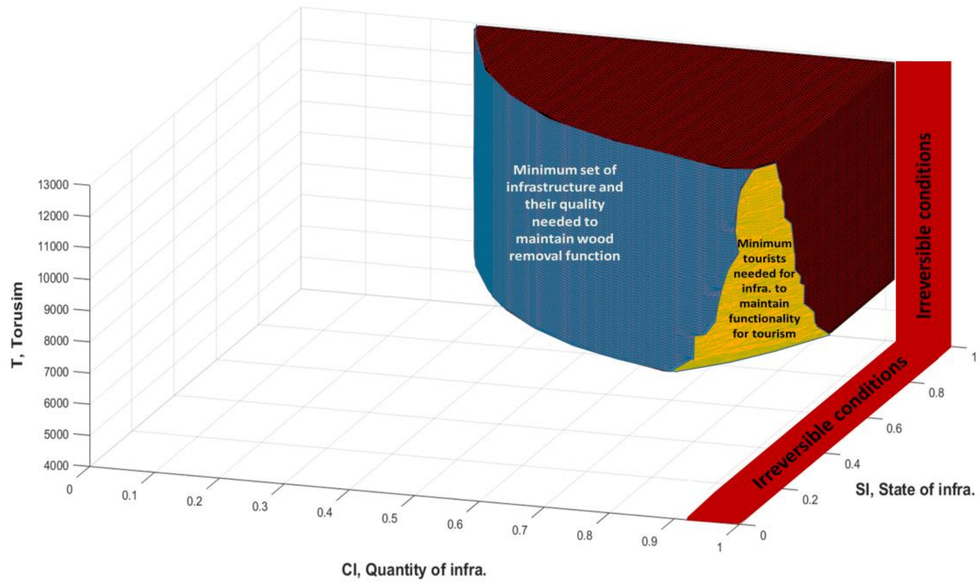

Figure 2. Viability kernel of the adopted multi-functional scenario showing the different non-viability conditions.

On one hand, Fig. 2 shows that the system is not viable for a low infrastructure quantity and states. Certainly, this is due to the constraint enforced upon the infrastructure enhancement function for wood extraction that forces infrastructures (both as to quantity and quality) to be above a certain value (blue markings). On the other hand, as shown previously, crossing some threshold or tipping point doesn't permit tourism to be maintained and as a result (red area), it will lead to the deterioration of both functions.

Moreover, one can observe the non-viability of the system at the threshold of irreversible conditions (yellow markings). Indeed, as mentioned earlier, tourism principally contributes to the budget that is needed for the development of the infrastructure network. However, for a high quantity of roads and state in which it is not initially enough, a greater budget is essential to be able to maintain the states, which requires tourist numbers to be higher at initial states, hence the non-viable states.

3.3 Adaptive management

The scenarios approached in this article allow representing the impact of infrastructure provision strategy on the nature and performance of multi-functional forest management. The conflicts that occur between tourism and wood extraction functions in regard to the provisioning strategy can be minimized by choosing the best policy for the development of infrastructures. As it is the case with our previously developed scenarios, we adopted a provision strategy that is confined with $0 < \alpha_1 < 0.7$ and $0 < T_{C_F} < 0.3$, which ensures the continuity of building roads in the forest. However, according to the context and nature of multi-functionality, other infrastructure provision strategies may be more effective and adaptive in reality. To that end, we have decided to simulate the model according to provisioning strategies that are represented with $0 < \alpha_1 < 1$ and $0 < T_{C_F} < 0.4$ that allows in some context to halt the construction of roads. Figure 3 represents the changes in the sets between management of the two strategies mentioned in the tourism-oriented and multi-functionality oriented scenarios.

For low infrastructure quantities, one can observe that the system favors a strategy of constructing roads (yellow area) rather than maintaining for the reference scenario (red set in panels A and B). Notably, the infrastructure attractiveness function compensates, through improving the quantity of roads, the augmentation needed for the attraction of tourists. Outside the zones of minimum roads' state and quantity needed to function, the system is viable.

Nevertheless, for high infrastructure quantity in the forest, one can see that the system favors the maintenance of roads over their construction (blue area). However, due to the irreversible effect of road quantity on the model, the infrastructural system cannot be maintained in the case of low quality in regard to the number of tourists reached, hence the non-viable states.

As in regard to the multi-functionality scenario (green set), at a relatively low quantity of infrastructures, the two strategies provide the same safe operating space. However, the strategy with no road construction offers a small, but significant enlargement of the safe operating space in the area of low states and high quantity that is close to the threshold of irreversible conditions. Indeed, with a maintenance favoring strategy, constructing roads is less promoted in the forest which doesn't facilitate the transition of the system to irreversible condition states, and the viability kernel enlargement accordingly.

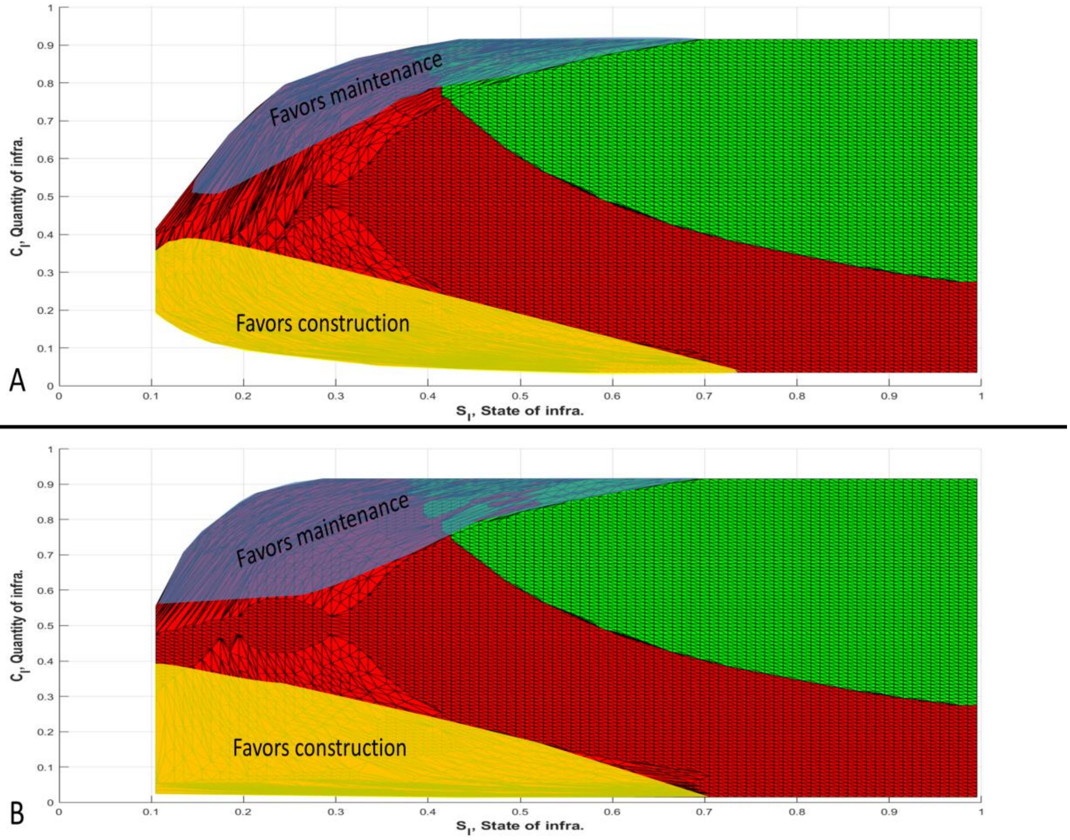

Figure 3. Viability kernel of the previously two studied scenarios (2D view): reference scenario (red) and multi-functionality scenario (green). Panel A represents the simulation of scenarios according to control that ensures the construction of roads, while panel B that of control that allows the halt of construction. Indications of infrastructure preference policy were qualitatively illustrated by blue and yellow markings.

4. Discussion and conclusion

We presented a viability analysis that takes into account a 3D dynamical problem that focuses on the multi-functionality problem. Through our analysis, we have highlighted two infrastructure provision strategies, in which it highlights the resilience of the maintenance strategy over the construction strategy for tourism management. We conclude by discussing the following points: (1) safe operating space for tourism through infrastructures; (2) safe operating space for multi-functionality; (3) adaptive management policies of two infrastructure provision policies.

4.1 Tourism through infrastructures

Tourism management is a critically important issue for forests, promoting the recent development of new decision-making tools [Bousset et al. 2007]. Tourism can be managed by carefully planning infrastructure provision strategies [Dillip 2012]. Management of the tourism function through infrastructures can be approached in two different ways: by building new roads for accessibility, and maintain existing roads in which it would require a minimum set of roads to be present. Both strategies are dynamically considered here. This study (figure

1) showed that beyond a certain number of roads, the functionality of the system in regard to tourism deteriorates reaching an undesirable outcome. This “tipping point” by which infrastructures threatens the performance of tourism in the forest has been previously highlighted by Sunlu [2003] by which the author identifies the environmental impacts of infrastructure development on the forest. Such impacts lead eventually to gradual degradation of the environment, and consequently, gradual decrease in the perceived attractiveness of the tourists. This identifies a cultural tipping point [Fernández-Giménez et al. 2017] that leads to a dysfunctional performance in tourism.

4.2 Multi-functionality through infrastructures

Conciliating the management of tourism with the management of wood extraction imperatives thorough infrastructure provisioning requires specific management tools to help design relevant policies. Our analysis (figure 2) showed that multi-functionality can be maintained within the defined safe operating space included in a framework of multi-criteria objective. Identifying the set of safe minimum standards in which within the system is viable is the first challenge of operationalizing multi-functionality. With our model, we have highlighted the threshold of dysfunctionalities of tourism with regard to infrastructures, in the presence of a wood extraction objective, highlighting the multi-functional role. Indeed, the analysis shows that enable to maintain the performance of multi-functionality the governance has to consolidate both high infrastructures quantity and the quality, as to which it doesn’t cross the threshold of irreversible cultural perception of the forest. Notably, this objective has been widely adopted by forest governance in several areas [Picchio et al. 2018]

4.3 Adaptive management through infrastructures

The study done here investigated a safe operating space for forest sustainability based on two policy controls. The first is tax imposition which created a budget for infrastructure provision, and the second is the ratio of the budget allocated for maintenance and construction of infrastructures. Together, these policy levers may help offer more flexibility [Mathias et al. 2015] in forest management. In particular, different approaches regarding these controls may lead to a more resilient forest system. Figure 3 represents the results of two different policies for infrastructure provisions, in which it highlights trade-offs that may occur between maintenance and construction favoring strategies. Indeed, Sunlu [2003] discusses the many effects infrastructures have on the ecology and landscape of the forest. On one hand, this demonstrates the drawbacks of building roads in contexts of high infrastructure abundance. On the other hand, having lower infrastructures limits the performance and development of forest functions [Ramage et al. 2017, Referowska-Chodak 2015]. This highlights the trade-off of maintenance and construction strategies, given minimal and maximal quantities of infrastructures.

Moreover, as mentioned earlier, the no-construction strategy shows a small augmentation in the safe operating space for multi-functional management with high infrastructure abundance, highlighting the preferred policy of maintaining the set of infrastructures rather than building new ones. Indeed, building roads in forests has been one of the most recognized problems [Sunlu 2003, Caliskan 2013] for their management. On one hand, accessibility infrastructures are needed for the performance and development of forest functions within the recreational framework (i.e., accessibility to ski resorts) or the wood extraction context (i.e., facilitation of wood mobilization). On the other hand, their impact on ecology and biodiversity is too significant to be ignored [Caro et al. 2014]. It is thus important to identify the minimum quantity of infrastructures in the forest while maintaining an increasing performance of functions.

4.4 Conclusion

Although the problem of forest multi-functionality addressed here considers only two functions in the forest, the trade-offs identified between these functions have been highlighted by the significant change in safe operating spaces. Therefore, this calls for a need to develop strategies that are able to consolidate, through infrastructure provision strategies, the difference between the corresponding safe operating space for tourism and wood extraction function, respectively. We have tested two approaches for infrastructure provision (construction and maintenance favored policies), and however, found that in forests, the impact of maintaining a minimal set of infrastructures offers a more sustainable and resilient approach than that of building. This offers an insightful view on adaptive management strategies in forestry. However, there is a need for a far more sharp viability analysis that takes into account the dimensionality and the dynamics of forest structure and biodiversity respectively. Finally, using viability theory for assessing SOSs seems to be a promising approach for addressing contemporary issues of multi-functional social-ecological systems.

Acknowledgments

This research has been funded by the ANR (Agence Nationale de la Recherche) under the VIRGO project (ANR-16-CE03-0003) and the region of Auvergne. Moreover, this research was conducted on the Long-Term Socio-Ecosystem Research platform LTSER “Zone Atelier Alpes”, a member of the ILTER-Europe network.

References

At the end of the manuscript

Supporting Information for

[ADAPTIVE MANAGEMENT OF INFRASTRUCTURES TO OPERATIONALIZE MULTIFUNCTIONAL SAFE OPERATING SPACE]

[M.HOUBALLAH[1], JD MATHIAS[1], T.CORDONNIER[2]]

[[1] Université Clermont Auvergne, Irstea, UR LISC, Centre de Clermont-Ferrand, 9 avenue Blaise Pascal CS 20085, F-63178 Aubière, France.[2] Université Grenoble Alpes, IRSTEA, UR LESSEM, 38000 Grenoble, France.]

Contents of this file

Appendix 1

Introduction

The main purpose of viability theory [Aubin 1991] is to explain the evolution of the state of a control system, governed by non-deterministic dynamics and subjected to viability constraints, to reveal the concealed feedbacks that allow the system to be regulated and provide selection mechanisms for implementing them. It assumes implicitly an "opportunistic" and "conservative" behavior of the system: a behavior that enables the system to keep viable solutions as long as it's potential for exploration (or its lack of determinism) - described by the availability of several evolutions - makes possible their regulation.

Viability theory is described as a mathematical theory based on three main features, namely: (i) non-determinism of evolutions, (ii) viability constraints, and (iii) inertia principle. The two first features concern the state trajectory of the studied system and reflect the fact that a system can evolve in many different and possibly unpredictable ways depending on its initial state, its past evolution, the environment in which it evolves or anything else (non-determinism), and also the fact that, for many reasons, the evolution of a system is restrained by some constraints that must be satisfied at each instant of time. These are the two founding pillars of viability theory models. The last feature (inertia principle) concerns the control variables and stipulates that these controls are changed only when required for maintaining viability. The system is considered not viable if the choice of control does not allow it to be maintained in the domain of constraints. To find a viable solution (or a set of viable solutions), viability theory follows a backward (or inverse) method, that is, starting from a set of given viability constraints, one looks for the set of initial states from which the system can be

indefinitely viable. In general, in deterministic cases, a lot of different control strategies are possible for maintaining the system in the constrained domain, which is the difference with the optimal control approach that proposes to find an optimal unique solution.
As mentioned before, in the viability framework, an important innovation is to introduce controls to explicitly account for the possibility to act on the system: controls are not fixed beforehand. Indeed, the purpose is to find suitable strategies that will maintain indefinitely the properties of the dynamical system within K. In discrete-time, this means that at each time step, there is a set of possible controls that one must choose from. A dynamical deterministic control system can be written, in discrete time, as follows:

$$\forall t \geq 0, x(t+dt) = x(t) + f\big(x(t), u(t, x(t))\big)dt$$

Where $x(t) \in X$ is the state of the system at instant t. The space of state X is a subspace of R^n, where n is the number of dimensions of the problem. At each time step, the dynamic f of the system depends on the control $u(t, x(t)) \in U(t, x)$. This control, taken at time t based on the state in which the system is found in, influences the dynamics at the next time step. The space of controls $U(t, x)$ is generally discretized belonging to a subspace of R^q where q is the number of discretized values of available controls.
We then define the set of constraints $K \in R^n$ in which we want to maintain the system. We will say that the evolution of the system is viable if:

$$\forall t \geq 0, x(t) \in K$$

The viability theory makes it possible to determine how to choose the actions at each moment in order to satisfy the constraints in a sustainable way. The major concept of this theory is the viability kernel. It is the set of initial states of the studied system for which there exists at least a sequence of controls maintaining the system in the constraint domain, up to a given time horizon. The viability kernel is written:

$$Viab(K) = \{x(0) \in X \ such \ that \ \exists u(.), \forall t \geq 0, x(t) \in K\}$$

Thus, if the initial state $x(0)$ of the system is not in this viability kernel, its output from the constraint domain is unavoidable. On the other hand, if its initial state is part of the viability kernel then there is a possibility of keeping the system in the constraint domain.

The viability kernel provides important information about the system being studied [Aubin 2002]. For example, if the kernel occupies the entire constraint space, regardless of the initial state of the system, we will have solutions to maintain its properties. On the other hand, if the kernel is empty, this implies that the current system is not viable as it is the case in [Domenech et al. 2011] and other management options need to be explored.

Figure S1 summarizes these concepts.

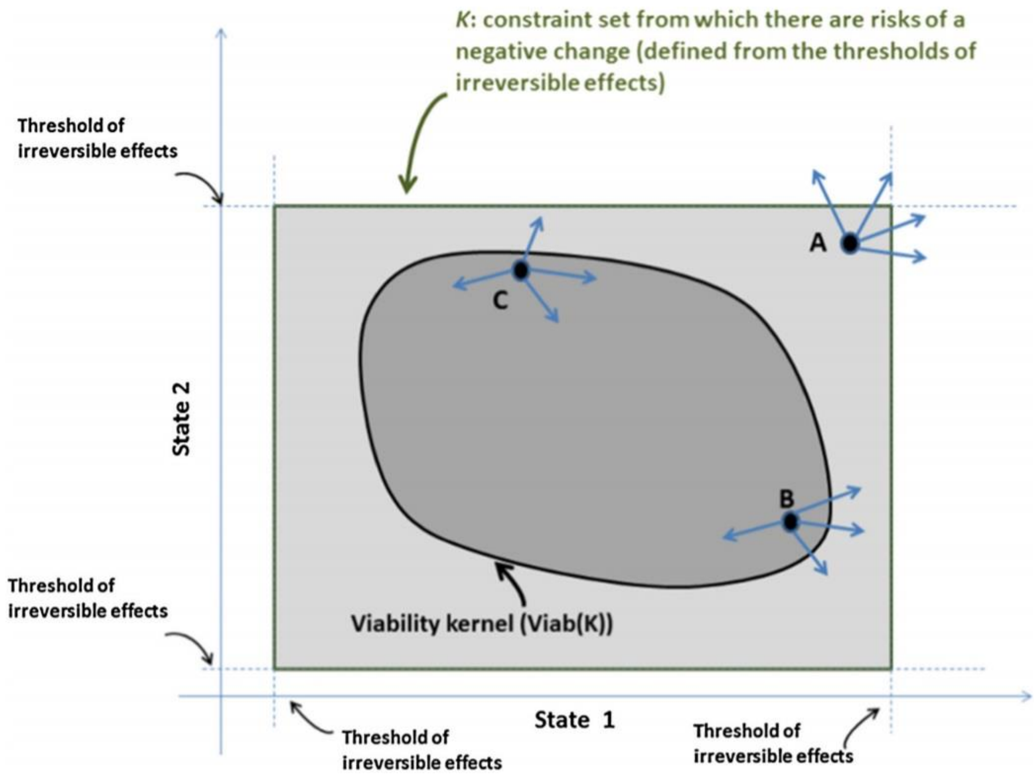

Figure S1. The constraint space K is defined from thresholds of irreversible effects. The viability kernel corresponds to the zone where there is at least one policy option able to keep the SES within K. At point A, there is no strategy able to keep the system within constraint set K. At points B and C, there is at least one strategy that ensures the system stays within constraint set K.

Appendix 2

Introduction

The following table represents the parameter used in the model and their values for the simulation.

Parameters

Symbols	Reference	Definition	Unit	Range/value
$\boldsymbol{H^F}$	Muneepeerakul and Anderies 2017	Infrastructure enhancement function	C_I	$[0-1]$
$\boldsymbol{H^T}$	Muneepeerakul and Anderies 2017	Infrastructure attractiveness function	$\left[\frac{1}{t}\right]$	$[0-1]$
$\boldsymbol{h_m}$		Wood removal objective	$\left[\frac{m^3}{C_I}\right]$	10
$\boldsymbol{\delta}$		Depreciation rate of infrastructure	$\left[\frac{1}{S_I}\right]$	0.05
$\boldsymbol{S_{I_0}}$		Threshold of S_I below which	$[S_I]$	0.1

		H^F is zero		
$\boldsymbol{S_{I_m}}$		Threshold of S_I above which H^F is maximum relative to C_I	$[S_I]$	0.9
$\boldsymbol{S_{I_{0T}}}$		Threshold of S_I below which H^T is zero	$[S_I]$	0.01
$\boldsymbol{S_{I_{mT}}}$		Threshold of S_I above which H^T is maximum relative to C_I	$[S_I]$	0.4
$\boldsymbol{T_{c_F}}$	none	Tax contribution of wood removal users to the government	$[-]$	$[0.1 - 0.4]$
$\boldsymbol{T_{c_T}}$	none	Tax contribution of tourism users to the government	$[-]$	$[0.1 - 0.2]$
$\boldsymbol{p}$	Memoire Bachard 2011	Price of $1\,m^3$ of timber	$[\$]$	50
$\boldsymbol{c_m}$	Memoire Bachard 2011	Cost of extracting $1\,m^3$ of timber	$[\$]$	21
$\boldsymbol{\alpha_1}$		Ratio of the budget targeted at construction of roads	$[-]$	$[0 - 1]$
$\boldsymbol{u_1}$	Muneepeerakul and Anderies 2017	The effectiveness of investment in the construction of roads	$\left[\frac{C_I}{\$}\right]$	4
$\boldsymbol{\mu}$		The growth per unit of road	$[\frac{1}{C_I}]$	0.0005
$\boldsymbol{\alpha_2}$		Ratio of the budget targeted at maintenance of roads	$[-]$	$[0 - 1]$
$\boldsymbol{u_2}$	none	The effectiveness of investment in the maintenance of roads	$\left[\frac{S_I}{\$}\right]$	0.2
$\boldsymbol{C_{I^{max}}}$	none	Maximum value for roads on the forest	$[C_I]$	1
$\boldsymbol{a}$	Casagrandi and Rinaldi 2002	Expected attractiveness of the forest	$[-]$	0.1
$\boldsymbol{\alpha_T}$	Casagrandi and Rinaldi 2002	Ratio of congestion of tourists	$[-]$	9×10^{-5}
$\boldsymbol{a_T}$	none	The maximum attractiveness	$[-]$	1

		related to the road availability		
C_{I_0}	none	The number of roads in which the perception of tourists is considered the highest	$[-]$	0.5
c_T	none	The rate of increase/decrease in attractiveness when increasing the number of roads	$[-]$	1
π_T		Revenue ratio collected from the tourists	$\left[\frac{\$}{T(t)\times t}\right]$	1
B_A		Annual budget calculated from the taxes of functions	$\left[\frac{\$}{t}\right]$	$\sim[0-1000]$
I_{BA}		Ratio of the budget for provisioning of roads	$[-]$	0.5
k		The rate of decrease in road maintenance effectiveness	$[C_I]$	80
ε		The number of roads introduced at time t.	$\left[\frac{C_I}{t}\right]$	$[0-1]$
x_1^0, x_2^0		the assumed most attractive forest structure for tourists	$\left[\frac{x_1}{ha}\right], \left[\frac{x_2}{ha}\right]$	$200, 400$
$\omega_1, \omega_2, \omega_3$		the rate of change of the forest attractiveness	$\left[\frac{1}{x_1}\right], \left[\frac{1}{x_1 x_2}\right], \left[\frac{1}{x_2}\right]$	15×10^{-4}, -7×10^{-5}, 9.9×10^{-5}

Table S1. Definitions, references, dimensions, and values of parameters found in the model.

Chapter 5

Conclusion

5.1 Overview

During this thesis, we have explored different tools and frameworks that allow us to approach forests as complex SESs and address their sustainability. These practical explorations are illustrated with an application of a real case study of sustainable forest management, the Quatre-Montagne forest located in the Vercors national regional park in France. The interest of this work lies in the infrastructure focus that we believe has gained a lot of interest in recently published literature. The complementary application of the SES and robustness frameworks introduced in **Chapter 2** has allowed us to conceptually represent the link between the SES framework's interaction (I) and outcomes (O), with a special focus on the role of infrastructures in mediating interactions. The picture that emerges from this methodological application shows that careful infrastructure investment strategies are needed in order to closely enable multi-functional forest management. A significant result of this application lies in the qualitative representation of spillovers that can play a significant attribute in the outcomes of any interaction mediated by infrastructures. This is an essential concept to adopt [Anderies 2016], especially when contemplating a multi-functionality role of forests. When managed, spillovers may enable the multi-functionality role due to the multiple level effects that can happen from the presence of infrastructures and their interactions. This work paves the way towards an inauguration of the multi-functionality concept within the SES framework.

The conceptualization of multi-functionality management of forests through the complementary framework application has allowed tackling problems of sustainability. The understanding of interactions between the social and ecological aspects of forests, along with addressing their complexities, is an essential part of approaching their sustainable development analysis. This opens the door for the utilization of practical and integrative mathematical tools that allow for studying sustainable management of forests. The main base of these tools lies in a careful "translation" of the conclusions and ideas of the qualitative analysis into a mathematical model. The idea resides in building the model following the conceptual representation of multi-functional management. This modeling approach has been used by Muneepeerakul and Anderies [2017], which holds value in operationalizing the robustness framework. In its context, **Chapter 3** introduces a model that explains the interaction of different forest functions (wood removal, tourism, and biodiversity) in the presence of an infrastructure enhancement function, which links their exploitation performance to the existence of infrastructure based on the qualitative results in **Chapter 2**. The results of the model exploration focus and highlight the many tradeoffs in the functionality of each forest service. Maximizing one function can incur negative effects on the functionality of others. The governance, being an infrastructure provider, can play an important role in maintaining and developing the functions without affecting the overall economic, social, and ecological performance of the forest. Despite its global understanding, the problem of long term and short term effects of management strategies has been largely unknown [Hunter et al. 2011]. The model explores this trade-off and shows that there is a clear interplay between social and economic functions. On one hand, a short term management strategy can be beneficial for economic functions but shows a clear effect on the ecology of the forest which applies a direct negative effect on social functions. On the other hand, long term management strategies decrease the economic performance of the forest and recognize the sustainable management of the forest. However, the model analysis concludes that the drawbacks of both approaches can be minimized by designing infrastructure provision strategies that enable economic performance to the point it would not have a grave effect on the performance of forests.

Furthermore, the recognition of climate change problems has made the concept “adaptation” strategies at the center of the scientific discussion for sustainable management of ecosystems [Bohnet 2010, Millar et al. 2007, Pahl-Wostl 2007]. With an infrastructure approach for management, we sought to explore in **Chapter 4**, with integrative tools, the extent of the model to define adaptive management strategies. Because of the congruence of viability theory with the objectives approved by goals of sustainability, adaptive management, and safe operating space concepts [Mouysset et al. 2018], we have decided to explore its application in forest multi-functionality with road provision controls. Its application to the infrastructure mediated interplay between tourism and wood extraction highlighted the trade-offs that can occur between decisions of construction and maintenance in different contexts. The analysis identified a critical state that is defined by a threshold by which if crossed, can lead to negative outcomes on the multi-functionality of the forest. However, the behavior of the system at the boundaries of the threshold can be altered by endorsing an adaptive strategy that includes a no-construction of infrastructures approach.

5.2 Perspective

Many of the most pressing threats to forests result from complex interactions between multiple stressors and require management on large spatial and temporal scales. Although spatial and temporal location determines the context for social and ecological dynamics, interactions can create dynamic feedback loops in which humans both influence and are influenced by ecosystem processes [Cumming et al. 2006]. For that, a peculiar challenge rises from managing forest landscapes as social-ecological systems that stem from mismatches in the temporal and spatial scales on which ecological and social systems typically function [Fischer 2018]. One of the social processes leading to a significant mismatch in such contemporary systems is the changes in infrastructures [Cumming et al. 2006]. Particularly, there has been a huge increase in the amount of infrastructure, making forests more accessible than ever, accumulating the rate of complex interactions [Forman 2000]. Our work can be useful in addressing this issue of mismatch as it directly considers infrastructure’s effect on forest multi-functionality performance. In particular, an important issue to address here is the temporal and spatial mismatches that occur at the threshold and tipping points of infrastructure provision that leads to irreversible conditions where the system starts to degrade. For example, what seems like a tipping point at a high temporal scale for infrastructure provision might be in fact a cascading failure of natural and human-made infrastructures for a smaller and appropriate scale. Notably, as forests change at various scales [Reyer et al. 2015], it is increasingly important to understand whether and how such changes lead to reduced resilience and potential tipping points. Understanding the mechanisms underlying forest resilience and tipping points from infrastructure provision view would help in assessing risks to ecosystems and presents opportunities for ecosystem restoration and sustainable forest management. However, in order to address this issue in our context, further development is needed in the constructed model to include complex feedback dynamical effects of biodiversity processes on the natural regeneration of the forest that is essential to report feedback effects on the environmental forest aspect.

A *sine qua non* condition for sustainable multi-functional forest management is the broad policies that identify sustainable development as an overall priority across all sectors [Osborne et al. 2015]. Forest policies deal specifically with forest resources and their management when treating: socio-economic factors related to increasing the performance of each sector, the role of the forest and tree resource in land use and rural development, and nature conservation and environmental protection. Today forests must be managed in a much more interdependent and complex context, which requires a partnership process among all major actors and beneficiaries [Schmithüsen 2008]. For this to happen, it is essential that forest policies recognize the diversity of interests related to forest conservation and utilization as well as the need to involve major interest groups in forest management decisions through consultations in which they can express their expectations and their role in sustainable forest management [La Notte 2008]. This calls to attention the importance of soft infrastructures and their role in sustainability on the multi-functionality level. The work done in this thesis has allowed for a preliminary inauguration of the concept of human-made infrastructure in a multi-functional context, and allowing for a mathematical analysis of the non-linear behavior of hard human-made infrastructures. The operationalization of soft human-made infrastructures within integrative tools remains one of the obstacles toward a better understanding of sustainability management of forests and natural resources in general [Hawkins and Wang 2013].

One of the pressing matters that forest sustainability addresses is the issue of climate change that has gained a lot of fame in recent decades [Keenan 2015]. It is also a major environmental issue that needs innovative thoughts, actions and most importantly serious collaborative efforts among different stakeholders involved [Sun and Yang 2016]. A perspective of our work is to address climate change as an exogenous effect on the forest social ecological system, with a special focus on the role and nature of infrastructures. Forests and climate are intrinsically linked: forest loss and degradation is both a cause and an effect of our changing climate [Popkin 2019]. The high degree of variability and uncertainty of climate change has induced the European Union, through the 2009 White Paper, to ask the member states to develop mitigation and adaptation strategies, with both hard and soft measures referring to infrastructures. In particular, for forestry, mitigation strategies should take into account appropriate rules and adaptation measures to reduce the vulnerability of forest ecosystems in relation to climate change, while emphasizing the role of forests in local economies. However, addressing adaptive management strategies from an integrative mathematical tool view needs to be based on a prior understanding of the approached system [Convertino et al. 2013], not just of the biophysical processes that happen in forests, but also of the social interactions that can define the outcomes of the system. This could be achieved through a comprehensive infrastructural system analysis approach addressing both their hard and soft nature. An integrated management system that ensures a steady flow of services is essential in the face of uncertainties of global climate change. Although this thesis adopts such an approach, more research works should be done in developing such methodological based model constructions, which has the potential to be used as a national-level planning tool.

"Essentially all models are wrong, but some are useful"

Box and Draper 1987

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