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Roxane Sansilvestri, Marlène Cuccarollo, Nathalie Frascaria-Lacoste, Marta Benito-Garzon, Juan Fernández-Manjarrés. Evaluating climate change adaptation pathways through capital assessment: five case studies of forest social-ecological systems in France. *Sustainability Science*, 2020, 10.1007/s11625-019-00731-7. hal-02297647

HAL Id: hal-02297647

<https://agroparistech.hal.science/hal-02297647v1>

Submitted on 11 Jul 2023

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<https://doi.org-10.1007/s11625-019-00731-7>

Original Manuscript

Evaluating climate change adaptation pathways through capital assessment: five case studies of forest social- ecological systems in France

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Manuscript submitted to Sustainability Science

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Abstract

Forest social-ecological systems (FSESs) can play a major role in both the mitigation of climate change, as well as the adaptation of local communities to it. In Europe, however, forests are highly fragmented and located close to human populations. This means that maintaining forest sustainability implies not only increasing ecosystem adaptation but also developing social adaptation. Hence, there is a need to understand the current priorities and management goals of forestry stakeholders, as well as their capacity to achieve functional and sustainable FSES in the future. The present study uses an interdisciplinary approach to evaluate stakeholders' capacity to deal with climate change and top-down policies in different FSESs. We selected five FSESs in France that exhibit a range of climatic threats and socio-economic characteristics to estimate their adaptive capacity and transformative potential. The estimation is based on an assessment of different types of capital (i.e. natural, social, resources, governance) that involves evaluating 70 indicators through more than 70 semi-structured interviews with local stakeholders. Our results highlight that forest management in France, and more broadly in Europe, is mainly based on technical approaches, which build stakeholders' confidence in their capacity to maintain the status quo. We observe asymmetry in capital distribution in some FSES, mainly through the maximization of the resources capital, which can constraint FSESs in a robustness trap. To develop adaptive capacity for small perturbations as well as transformability, forestry stakeholders should be encouraged to compromises. More balanced capital distribution, with decreased economic benefits, along with new technical approaches and changes to the landscape composition could be necessary to ensure the long-term adaptability of FSES to climate change.

Introduction

In Europe, forests are frequently located in close proximity to human settlements, making them part of the population's collective memory. Large-scale deforestation events have been followed by massive afforestation and successive waves of land abandonment, resulting in a complex landscape matrix (Papillon 2014). In addition, European forests are subject to rules regarding species used in each region, which are intended to preserve uniquely adapted tree populations under a stable climate (Fernandez-Manjarres and Tschanz 2010; Brang et al. 2014). However, rapid climate change is modifying stakeholders' perceptions regarding the established management paradigms. On a daily basis, stakeholders need to evaluate whether their inherited cumulative knowledge and the intricacy of local and European regulations are still relevant for adapting to the emergent forest conditions (Schultz 2008). In this paper, we consider coupled natural- human systems (Liu et al. 2007) in which forests represent the key natural component of the system. Hereafter, we refer to this kind of system as a forest social-ecological system (FSES).

For FSES, the development of adaptive strategies represents a significant challenge because of the very large spatial and temporal scales of their cycles, as well as the strong economic and social influences (Arnould et al. 2002; Papillon 2014; Pottier 2014). Resource management options such as the selection of trees for planting need to be suitable for 100 years or more and not only for the next 30 years (Loarie et al. 2009; Aitken and Whitlock 2013). In France, forests cover 30% of the total landmass and continue to expand in terms of area (+ 0.6% annually since 1980, Institut National de l'Information Géographique et Forestière 2017), which implies that human and forest areas increasingly lie in close proximity to one another. As a result, the social and economic aspects of forests are strongly integrated into forest management choices for rural areas in France (Boutefeu and Arnould 2006; Husson 2006; Barthod 2015).

From a historical perspective, modern French forestry emerged in the 1960s with the creation of the National Water and Forest School, which imposed a technocratic vision of forest management (Thoening 1973; Boutefeu and Arnould 2006). Management plans mainly focus on productivity and tree species development, particularly through genetic selection, based on a precise classification of climatic zones and soil types known as forest stations (National Forest Inventory 2011; Gaudin et al. 2016). Yet current climate change has created uncertainty among foresters. Indeed, foresters still use historical and technical knowledge mostly developed in the twentieth century to manage forests (e.g. species selection, seed sources, species mix, rotation times, densities). However, at the local scale, scientific and social uncertainties are growing and there are concerns about how current knowledge could be no longer sufficient (McCarthy and Burgman 1995; Wang et al. 2012; Brang et al. 2014). Today, foresters need to draw on new tools and knowledge, but they are often unaware of what will be useful to achieve sustainable FSES in the future (Bolte et al. 2009; Brang et al. 2014; Lefèvre et al. 2014). The concepts of sustainability, adaptive capacity (AC), and resilience are interrelated (Smit and Wandel 2006). Their application in efforts to adapt areas to new conditions presents enormous challenges largely due to the fact that it remains unclear which conditions favor these system characteristics. In this paper, we consider that the AC of stakeholders can be defined as a gradient of strategies (Millar et al. 2007) consisting of (1) the coping strategy (robustness), which relates to the persistence of the initial ecosystem (Anderies et al. 2004); (2) the resilience strategy, which reflects the capacity to absorb perturbations and remain functional (Holling 1973); and (3) the transformative strategy, which has more recently emerged in the literature and involves fundamental changes in the system with crucial shifts in values, patterns, and paradigms (Olsson et al. 2014).

High AC is a particularly desirable property to enable FSES to adapt to new conditions (Folke et al. 2002; Berdoulay and Soubeyran 2014). Adaptive capacity is a multidimensional property of all social-ecological systems, and it depends on the diversity of social, economic, political, and ecological assets (Walker et al. 2004; Folke 2006; Magnan 2009; Williamson et al. 2012). In principle, well-developed capitals could enhance the AC to ensure smooth transitions and avoid irreversible shifts in the face of long-term and diffuse perturbations such as climate change, as well as more periodic perturbations such as storms or floods (Szreter

and Woolcock 2004; Tompkins and Adger 2004). As capital represents the available stock of material and non-material elements (Bourdieu 1986; Ostrom 2009), a minimum amount of capital allows a system to be maintained in a sustainable condition when disruptions are small (Godard 2010). However, when the pressure of disruption is too strong, high levels of capital are necessary to develop greater AC and allow the system to transform. Thus, the social-ecological system will change according to its own capital stocks, societal priorities, and what is considered socially tolerable or unacceptable (Godard 2010).

As a result, adaptation strategy chosen based on technical possibilities and social priorities will most likely differ between different social-ecological systems (Godard 2010).

For this paper, our overall objective is to estimate the AC of five FSESs through the evaluation of the locally available capitals and highlight the conditions of the emergent AC. To reach this objective, we formulate three specific questions: (1) What are the key factors contributing to the development of AC in FSES?; (2) How do these factors vary between forest regions with different environmental conditions, land-use histories, and governance?; (3) Which factors support or impede transformability in the face of perturbations?

We select five FSESs in France with different combinations of economic, political, cultural, and ecological characteristics along a climatic gradient. These include an Atlantic (Landes forest), Mediterranean (Var forest), Alpine (Northern Alps), and two temperate regions (Fontainebleau and Morvan forests) FSESs.

Our work forms part of the general adaptation analysis of different regions and focuses on the relative AC of specific regions through a comparative analysis based on indicators and criteria preselected by the authors (Smit and Wandel 2006). We use our own interpretation of capital assessment (Wilson 2010; Jarzebski et al. 2016), based on the evaluation of indicators to estimate AC at the local level. To estimate AC by evaluating the capitals of our five chosen FSES, we combine approaches from the social and natural sciences. Traditionally, the natural sciences adopt a positivist approach to study environmental issues, implying that local knowledge and views are validated based on objective or empirical observations (Moon and Blackman 2014). In our case, we also use climate predictions to estimate the impact of climate change on forest ecosystems, as frequently done in ecological studies. However, when studying coupled natural-human systems, positivist approaches cannot highlight all the mechanisms underlying nature-human relations (climate risks in our case), and especially the impact of human choices and reasoning (Evelya et al. 2008). This would require direct consideration of stakeholders' voices. Hence, we also relied on semi-structured interviews with local stakeholders and institutions to assess their capacity to deal with the current and future challenges caused by climate and environmental change.

Materials and methods

Study sites and institutional landscape

We selected five FSESs exhibiting a range of different climatic, ecological, cultural and socio-economic characteristics (Fig. 1). The Var forests correspond to the Mediterranean region and is characterized by high natural biodiversity, high exposure to climatic threats and conflicts between tourism and landscape conservation. Alpine forests are represented by the Northern Alps and illustrate mountain issues, especially related to technical and safety problems considering the steepness of the forest plots and the communication challenges between different valleys and stakeholders. The Atlantic forest, known as the Landes forest, is an artificial (almost) mono-specific forest created in the nineteenth century. Thus, the human-forest relation is very distinctive, considering that this specific type of forest cannot exist without human interventions. Finally, the two temperate forests represent the most widespread forest type in Europe. Fontainebleau forest is characterized by nearby dense cities with many recreational activities taking place inside the forest, not to mention its heritage status for urban citizens. The Morvan forest is a very dynamic forest region with economic opportunities and a strong cultural heritage of wood management.

The first step of the study selection process was a climate exposure analysis (explained in “Conceptual framework” below) to ensure that the selected regions were potentially affected by climate change (Fig. 2). The second step was to describe the stakeholder framework and governance system based on a heuristic model of the French FSES developed during interviews at the Ministry of Agriculture, Agrifood, and Forestry (P. Bouillon and . Poffet, pers. comm.). Using insights from these top-level policymakers, we identified key organizations and stakeholders involved in forestry governance in France (for more details, see Fig. S1 and Table S1 in the Supplementary Material). We were interested in institutions representing both the private and public sectors. However, as French forests are mainly private (70%), we focused on their governance and conducted most interviews with stakeholders from the private sector, mainly private forest owners, industrial stakeholders (e.g. sawmills, paper mills, firewood), and institutional stakeholders (e.g. local forestry offices, cooperatives, unions, associations). To ensure a good representation of local issues and interests, we conducted interviews with several respondents from different hierarchical levels within the same organization.

Conceptual framework

Considering the importance of climate change in long-term forest management, we used climatic exposure as one of the factors for the selection of case studies “Study sites and institutional landscape”. One of the indices for such a purpose is the general index of water stress used to classify climatic regions for seed management in North America. In short, a summer moisture index is calculated as the mean summer temperature (in K) divided by the mean summer precipitation (in mm), which provides a straightforward value to be compared between regions. We use temperature and precipitation data based on the average outputs of 11 global circulation models from the WorldClim database (http://www.worldclim.org/cmip5_2.5m) under the mid-strength RCP4.5 scenario. The index was calculated for both 2050 and the reference

climate (i.e. average conditions between 1950 and 2000). Next, the 2050 results are subtracted from those of the reference climate to establish temporal trends. Hence, our exposure index produces negative values for areas that will have less water stress in the future and values greater than one for those that will potentially experience increased water deficits. We arbitrarily decide that for a FSES to be eligible to be included in this study, the region should have a climatic exposure equal to or greater than one (Fig. 2). This approximately represents the threshold for the lowest 25% of all the observed values to ensure that regions with enough separation will be represented in the surveys. In fact, if we had used a more stringent threshold (e.g. 50% or 75%) more than half of the French territory would have been excluded. Analyses were performed using the Raster library in the R language for mathematical computing. The scripts are available on demand from JFM.

We employ a capital-based approach to evaluate the AC of the FSES (Bourdieu 1986; Walker et al. 2004) based on the perceptions of stakeholders elicited through more than 70 interviews (see “Data collection and analysis”). In our analysis, we use the term “capital” to define a stock of accumulated elements (material or non-material) at a specified time, and we describe each capital by components (referred to as “AC determinant” in Magnan 2014). Based on our own judgement and the description of the concept of capital in the literature (Folke et al. 2005; Walker et al. 2006; Gupta et al. 2010; Wilson 2010; Anderies et al. 2013; Jarzebski et al. 2016), we choose to focus on four types of capital: social capital (S), defined as the social networks, cognitive elements and culture (Olsson et al. 2004; Ravera et al. 2011; Magnan 2014); resources capital (R), defined as economic, human and technical resources (Ostrom 1990; Nelson et al. 2010; Magnan 2014); governance capital (G), defined as the official and non-official hierarchical organization and public policy planning (Olsson et al. 2004; Dedeurwaerdere 2005; Pahl-Wostl 2009); and natural capital (N), defined as the biological components and functioning capacities of the ecosystem (Ostrom 1990; Cardinale et al. 2011; Schultz et al. 2015).

We develop an analytical table to evaluate the different levels of AC-related capitals based on a series of postulates regarding the characteristics that would support AC in a FSES. We defined three general components per capital, with each component divided into a more specific list of indicators. For example, in the resources capital (R), the third component (R3) “technology and techniques” has four indicators that include “research investments” (R3a), “diffusion of commercial and industrial knowledge” (R3b), “experimental investment” (R3c) and “existence of local research center” (R3d). Our conceptual framework thus comprised a total of 70 indicators for each site (for more details, see Table S3 in the Supplementary Material).

Data collection and analysis

We use semi-structured interviews with questions focused on the four capitals to assess the AC of the five study FSES. The authors conducted interviews between August 2014 and

February 2015, and between November 2016 and April 2017. Each interview lasted between 60 and 90 min. The analysis of the interviews was based on stakeholders' responses as transcribed and interpreted by the authors in accordance with the traditional interpretive social science research method (Gomm et al. 2000). In particular, our research approach falls within the third category described by Smit and Wandel (2006), when assessing potential AC to help public policy decision-making.

To quantify the different capitals and estimate the potential AC, we adapt a method from the "adaptive wheel" (Gupta et al. 2010). Hence, we attributed indicator scores according to the stakeholders' responses as below:

- + 2 for a potential highly positive effect on AC;
- + 1 for a potential positive effect on AC;
- 0 if the indicator had no potential effect on AC (or was irrelevant to the specific FSES);
- - 1 for a potential negative effect on AC;
- - 2 for a potential highly negative effect on AC.

When conducting our analysis, we were well aware that evaluators can insert bias when interpreting information collected in the field by rating answers that concord with their own point of view or past experiences when attributing a score. To minimize this subjectivity, we adopt several quality assurance processes.

First, we use several answers from different questions to calculate the score of each indicator, meaning that there were more questions than indicators. For instance, to evaluate the indicator "Access and diffusion of knowledge" (S1a) we use, among others, the responses of different stakeholders to several questions such as "How do you learn forestry practices?", "Did you go to the forest with your parents when you were a child?", or "Do you speak about the forest and your forestry practices with your friends or neighbors?".

Second, we perform independent scoring, followed by cross-validation. In particular indicators were scored blindly in parallel by two of the authors (RS and MC). After a round of parallel scoring, the lead author looked for discrepancies between two scores and provided a compromise score if necessary. This process produced a table of raw results consisting 76 rows (one row per interviewee) and 70 columns (one column per indicator). Next, the scores of each indicator per site were averaged to get a single value per FSES. This averaging

produced a table of five rows, one for each FSES, and 70 columns, one per indicator (intermediate tables not shown). The scores for each capital component (i.e. three components per capital) and each one of the four capitals were obtained by adding the corresponding mean scores in each FSES (from the 5×70 table described above). The score of each component is derived from the sum of all its relevant indicators, which can vary from one component to the other.

Finally, the score of each capital is a cumulative score and corresponds to the sum of the score of the three components (Fig S2 in Supplementary Material).

Third, we carry out a simple size standardization of the final score data to avoid bias induced by the different numbers of interviewees in each site. During this process, we adjust the scores to the minimum sample size of interviews for each FSES. This is because they vary from 4 to 20 between the different FSES. In a nutshell, we bootstrap 100 times each FSES score results table for a sample size of $n = 4$ (sample size for Fontainebleau) and estimate the average score and additive score for each FSES. The standardization code was written in MatLab® and can be provided on request by JFM.

The assessment of natural capital slightly differs from what is usually measured in other studies in which only biological features per se are considered (e.g. biodiversity, tree productivity, extent). In our case, we are interested in these features in addition to the survival and reorganization capacities of a managed ecological system. Here, natural capital represents a description of the current state of the ecological system, its functioning, and its capacity to cope with disruptions based on current management knowledge (i.e. a managed social-ecological system and not an ecosystem in isolation).

Note also that the indicator scores that we use to evaluate natural capital are directly attributed by the authors and not based on an interpretation of the interview responses. Thus, natural capital includes aspects of national forest inventory data, which since 2005 has provided nationwide data on forest tree species composition, standing biomass, tree growth, and tree mortality for over 60,000 plots across France. Health forest reports are also used to evaluate the function, current state, exposure, and sensitivity of forests to estimate future risks and probable changes. We should also note that these scores represent the entire forest region as defined in the forest inventory, rather than the visited forest plots. For instance, for the indicator (N1a) “Specific diversity” (see Table S3 in Supplementary Material), we attribute + 2 for forest regions with 8 or more tree species found in the inventories, + 1 for 5–7 tree species, – 1 for 2–4 tree species, and – 2 for less than 2 tree species. We do not attribute a zero score to this indicator. Details on the natural capital scoring can be provided on request to RS.

Results and discussion

Our interviews involved more than 70 stakeholders. The overall results are summarized in Table 1 (for more details about the interviewees see Table S2 in Supplementary Materials). A preliminary analysis suggests that the stakeholders engaged in the forestry sector in the study FSES are rather old, with a mean age of around 50 years old. The recurrent major capital is the natural capital which suggests that forest ecosystems are in a good health, while the recurrent minor capitals are resources

and governance ones which suppose that stakeholders have difficulty getting themselves and the sector organized. Except for the North Alps FSES, the distribution of capitals varies substantially in all other FSESs, which could create imbalance in the AC of the studies FSESs, as described in the following sections.

Instead of analyzing all aspects on a case-by-case basis, we structure the “Results and discussion” by focusing on comparative elements that emerge, after compiling all the results and interview data.

The robustness trap: maximization of one capital type

It is widely believed that a good level of biodiversity (which tends to correspond to high natural capital), can promote AC in social-ecological systems (Tilman et al. 2005; Isbell et al. 2015). Similarly, the resilience literature, suggests that a well-organized community with good communication, trust, and knowledge (which tend to correspond to high social capital), tends to have high levels of AC (Adger 2003; Anderies et al. 2004; Nelson et al. 2007). Considering the above, we could expect that high natural and/or social capital could promote AC

in the study FSES. However, our analysis demonstrates that high capital levels can potentially limit local AC in some cases. In fact, any imbalance between capital levels can cause a limitation in adaptive trajectories. This imbalance is expressed in different ways according to the historic, cultural, and environmental conditions of the FSES, as discussed below.

Natural capital in the Mediterranean FSES

The Mediterranean case (i.e. the Var FSES) has high levels of natural capital (Fig. 3a), especially represented by its high biodiversity in rare and keystone species, and its regeneration capacity after fires (i.e. high score for ecological system characteristics in Fig. 4a). Historically, the Var FSES lacks a forestry culture, with the local economy traditionally growing due to mining and agricultural production. However, during the twentieth century, European and national authorities implemented strong public policies to protect the high level of local biodiversity. These decisions have consequently limited the development of forestry practices and related income sources for foresters (i.e. low technology and techniques in Fig. 4a).

This situation creates strong tensions between stakeholders inside the Mediterranean FSES. According to a respondent “In the Var, forests are considered to be forests that should be protected and, above all, should not be touched” (Forest manager ID60). Foresters feel constrained by regulations and deprived of their property. For example, one of the interviewees suggested, “There are more regulations than forests. Our hands are tied” (Private forest union member ID55). For instance, 27% of the Var forest surface is classified as a Natura 2000 area, and the region includes one national park (with very restrictive regulations) and two regional parks. Even though these regulations are not intended to exclude foresters from exploiting their forests, these stakeholders feel that their practices are not taken into account in regional planning.

Moreover, even if there is rich biodiversity, forest productivity remains low considering the harsh environmental conditions. As wood has a low economic value, foresters have difficulty benefiting from wood sales. Foresters must adapt their activities to protect local biodiversity, but they also lack an economic support system or alternative sources of revenue. Foresters feel betrayed and rejected, due to the priority given to tourism despite the fact that foresters offer many free services. As aptly described by a respondent, “In the Mediterranean, wood has no value, but the forest has a high value. Foresters want to receive subsidies to maintain forests and the associated ecosystem services” (Forest regional institution member ID52). Regional biodiversity protection policies, combined with the low income generated through forestry, constrain most foresters to do the strict legal minimum in terms of forest management. Thus, they avoid considering seriously new practices or trajectories (e.g. different landscape combinations of forests and crops), which eventually limits the local AC. Overall, foresters in the Var FSES consider the current situation to be a dead-end and do not seek to develop new knowledge or alternative economic activities, thus maintaining low levels of social and resources capital (Fig. 3a).

Social capital in the Fontainebleau FSES

We observe a similar situation in the Fontainebleau FSES, which presents a case of high social capital (Fig. 3b), explained by the historic and symbolic component of this forest. While the literature advocates the need to increase social capital as a means of improving AC (Adger 2003; Dedeurwaerdere 2005), the over-involvement of local citizens and stakeholders in the decision-making and management of this public forest can potentially slow down adaptive processes to new conditions.

As a public forest, Fontainebleau is managed by the National Forest Office, which benefits from a heritage status due to its long history. This forest was landscaped on dry sandy soil by foresters in the twelfth century for economic and military purposes. It was maintained during the seventeenth century for royal hunts and then painted during the nineteenth century by the great painters of the Romantic period. Fontainebleau forest is visited by 17 million people annually, mainly by nearby urban dwellers who perceive it as an old romantic forest in which one can walk freely. However, this high popularity creates problems. As one interviewee pointed, “Here, the major problem is that everyone who comes to Fontainebleau feels that

they own the forest” (Public forest manager ID2). Considering its special status and proximity to urban centers, there are many nature-based associations (i.e. very high stakeholder network and collective interaction, Fig. 4b).

At the same time, the FSES experiences important ecological problems. For example, there is high mortality of beech trees (*Fagus sylvatica*), which are very sensitive to water table levels, as well as the high senescence of trees (Public forest manager ID3 and pers. obs.). To preserve the landscape heritage, local associations do not want to replace and/or introduce new tree species, even though the current species are poorly adapted or senescent. Hence, forest managers are confronted with citizens’ expectations of a “natural” refuge in Fontainebleau forest. Moreover, timber production has been limited following the complaints of urban residents/visitors about tree harvesting, even though the role of the National Forest Office is to harvest public forests. Local forest management is not independent and depends mostly on ad hoc economic subsidies from the Ministry of Agriculture, Agrifood, and Forestry, thus creating inertia in the decision-making process (i.e. low investment capacity, Fig. 4b).

Overall, in the case of Fontainebleau FSES, the active involvement of citizens through social organizations and the cultural heritage of the forest have created a sort of sclerosis in the management of the FSES. This slows down the implementation of new social or political thinking to manage this reserve, in the face of environmental change.

High resources capital of the Landes FSES

The last case exhibiting the maximization paradox is the Landes FSES, which exhibits the highest resources capital (Fig. 3c). The historic economic success over many decades is due to the high profitability of the maritime pine industry, which has created a sound local economy (Arnould et al. 2002). However, this economic success comes to the detriment of natural capital. In particular in Landes, humans are an intrinsic part of the FSES, because the mono-specific plantations that characterize the region have poor natural regeneration. These non-natural emergent conditions have legitimized human interventions in the area, even if they decrease the natural capital (i.e. low score for current management, Fig. 4c). As one interviewee suggested, “Maritime pine is the best adapted species for our region, and we know how to manage it well. We have no reason to change” (Forest regional institution member ID6).

For almost two centuries now, local communities have considered this mono-specific forest of maritime pine as a heritage landscape, with the management of maritime pine currently being a cultural tradition rooted in the collective memory. One of the respondents mentioned that “My grandfather planted pine, my father planted pine, so I’m planting pine, and of course, my son will plant pine” (Private forest owner ID21). This productive forest and its associated profitable industry, have catalyzed fierce local competition for wood processing and created strong pressure from global markets. This limits other forest uses, as according to one respondent: “20 years ago, each small town had its own sawmill and local foresters; large

industry has now taken over all the market, and we cannot afford to compete with them”
(Forest

operator ID13). The strong focus of the local forestry stakeholders on maritime pine essentially hinders the emergence of alternative methods of timber production and commercialization, or even alternative uses such as natural resin extraction, which was once widespread (i.e. low score for human and economy, Fig. 4c).

Overall the historical management of this FSES has led to an appropriation of the forest system, which is not really recognized as a “natural” component, but more as a source of revenue and cultural heritage that does not necessitate the preservation/restoration of biodiversity, or other ecosystem functions and services.

Technical development does not ensure adaptive capacity

Overconfidence in resilience capacity to specific perturbations

As explained above, the historical environmental conditions of the Landes FSES have created overconfidence among local stakeholders in their technical ability to manage their forests. However, this overconfidence can curtail the emergence of transformative trajectories that can increase AC, e.g. through the selection of new species and different landscape management approaches. In 1999, the Landes FSES experienced catastrophic storms known as Lothar and Martin, which impacted more than 60% of the forest surface. In 2009, a third storm named Klaus destroyed around 50% of new tree plantations. After the first storms, Landes’ stakeholders developed numerous processes and protocols to clear out high quantities of storm-affected wood. They benefited from the Ministry of Agriculture, Agrifood, and Forestry’s subsidies, which created a major public debt that slowed or blocked all forest initiatives in France for many years.

After the lessons learned from the 1999 storms, Landes’ stakeholders adopting some appropriate management approaches that enhanced their resilience. For example, they rapidly reacted to the 2009 storm by using the strategies established following the 1999 storm. Thus, the Landes FSES was restored in 4 years after the 2009 storm compared to the more than 10 years needed after the 1999 storm (i.e. high technology and techniques, and action ability, Fig. 4c). Nevertheless, this high resilience capacity does not necessarily result in high AC.

In fact, this example highlights a very specific resilience to specific disruptive events, namely storms. It is difficult to ascertain whether the Landes FSES would have the same resilience in the face of other events such as droughts or nematode pests located at the border of the Landes region (Karnkowski and Sahajdak 2010; Nunes da Silva et al. 2015). It is important to note that many foresters sold their forests to farmers after being discouraged by the 2009

storm. Restoring the pine forests seems too demanding for ageing forest owners who lack certainty about the recurrence of storms, and that do not believe that there are more resilient species or landscape to storms or other future extreme events (i.e. weak perception and learning capacity, Fig. 4c).

In our opinion, local AC, in this case, is clearly limited by the pressure of timber markets, as well as the high specialization in maritime pine. Without diversification in terms of species, rotation times (currently about 35–45 years), and industrial activities, the economic sector of the Landes FSES appears to be trapped in the “robustness deadlock” (Anderies et al. 2004). Literature suggests that dynamic forest ecosystems contain diversified strata, ages, habitats, and species (Maclver and Wheaton 2003; Thompson et al. 2009). Thus, from an adaptation point of view, the focus on a mono- strategy (even if adequately managed by humans) constrains the development of AC (Fazey and Fischer 2009; Fazey et al. 2010).

Short-term goals in the Morvan FSES

The Morvan FSES is characterized by good health with no significant historical ecological impacts and well-developed technical and economic resources (i.e. all resources criteria are positive, Fig. 4d). However, current forest management choices raise crucial issues concerning the long-term AC. Between 1950 and 1960, the Douglas fir (*Pseudotsuga menziesii*) was introduced to France to reforest certain areas after the Second World War. This introduction created mono-specific Douglas fir areas inside a diverse deciduous forest region. Today, the maturity of these plantations coincides with a national demand of Douglas fir for wood construction. The first logging operations have created an economic boom for forest owners and operators, which allow for new investment in forests.

Regional foresters who were initially attached to deciduous forest landscapes are now increasingly investing in new mono-specific Douglas fir plantations. Many respondents attested to the comparative advantages of Douglas fir: “I believe in this species [Douglas fir]. It is well adapted and increases the economic value of our forests. This species is beautiful and very profitable” (Private forest owner ID35); “If we are authorized to plant Douglas fir, we would not ask any questions; we will even plant Douglas fir to replace other [native] resinous species. It is more profitable” (Public forest manager ID22).

As in the Landes FSES, stakeholders have developed specific management techniques for Douglas fir such as genetic selection and soil fertilization. However, the popularity of Douglas fir is turning the once-diverse forests into mono- specific plantations, thus raising many crucial long- term issues for social, natural, and resources capitals. For example, the transition from mixed forests to plantations is not well accepted by all regional stakeholders, as there is a fierce debate about the landscape-level impacts on local communities and the tourism sector. Moreover, recent logging operations have increased economic richness and created employment, but at the same time the recent installation of large industrial sawmills

has increased competition from external stakeholders investing in the region in a forestry sector that mainly began as family businesses.

Similarly to the Landes forestry model, this single- way strategy potentially reduces the number of possible future trajectories for the system (and as an extent its long-term AC). Thus, the stakeholders in the Morvan FSES are reducing their AC by developing only economic capital, which is still well-distributed among stakeholders, making this strategy socially acceptable. This short-term euphoric vision could be explained by the sense of security among the Morvan stakeholders, considering the lack of environmental/ecological forest problems in the FSES (i.e. good ecological characteristics, Fig. 4d).

For the moment, local people in the Morvan FSES benefit from a comfortable economic situation with high forest growth potential. However, it can be argued that the current high income does not ensure their long-term AC. Even if the low heterogeneity of capital distribution in the Morvan FSES could indicate good AC, stakeholders have to quickly develop awareness about future climatic risks as well as a multi-trajectory management to avoid the pitfalls of the “robustness deadlock” experienced in the Landes “Overconfidence in resilience capacity to specific perturbations”.

Mismatches between technology and natural capital caused by top-down decisions

In response to low tree productivity and low profits in Mediterranean FSES, a top-down wood-biomass energy strategy has been implemented to “boost” the forestry sector as suggested by interviews and participant observation. However, this new strategy is based on the industrialization of the forestry sector and represents a danger to local AC. This is because of the focus on a single intensive strategy (i.e. wood-biomass energy), which corresponds to the maximization of one capital. Currently, the Mediterranean forestry sector is underdeveloped, mainly because of its low productivity, which is around one-third that of the Landes as observed in the forest inventory results. Furthermore, the produced timber is largely used for basic processing (i.e. weak human and economy indicator score,

Fig. 4a), which generates limited profits. A stakeholder alluded to this by claiming that “Private forest owners do not want to invest money in their forests if they will not derive any benefit” (Forest manager ID57).

The main political argument in favor of wood- biomass energy plants in the region is the large forest surface and for the economic revitalization of the forestry sector. Hence, two large European- funded projects for the construction of wood- biomass-energy plants in the region are currently being completed. These two projects require 1030,000 m³ of wood annually to function, while the Mediterranean forests currently produce only 720,000 m³ of all wood types combined (Percheval 2014; OFME 2015). A major challenge posed to public institution and industrial engineers is how to extract more wood from the forests. One of the respondents

pointed that “In fact, we only use 2% of the regional forest production. We need to develop our harvest potential to respond to industrial demands” (Public institution member ID59).

However, local foresters are uncertain about the real biomass quantity available: “There is not enough wood for everyone. They talk about wood stands, but they do not take slopes and accessible roads into account” (Forest operator ID64). In fact, a large forest surface does not imply large timber availability. Here, political decisions are mainly based on European Union goals and technological overconfidence, with the lack of consideration of regional expertise and expectations creating gaps between regional needs and national political agendas (Dupuis and Knoepfel 2013; Mola-Yudego et al. 2017), which could drive the region to a social and ecological collapse.

To find timber resources, foresters will overharvest easily accessible stands in response to industrial demands (Fernandez-Manjarrés, unpublished data) with no guarantee that this wood-biomass energy sector can improve the regional economy in the long-term. Moreover, the lack of forestry culture in the region could result in inadequate management plans and thus not only decrease its current high natural capital but also further diminish its current low governance capital in terms of trust and solidarity between stakeholders. Finally, this non-regional strategy risks putting strain on natural capital (which is the region’s greatest asset) and thus on its resources capital.

The cost of transformability: compromises

The alpine FSES exhibits a homogeneous capital distribution, which implies a better AC, as multiple capitals are available for multiple potential trajectories (i.e. homogeneous capital distribution, Fig. 3e). The region also exhibits several capital components that are positive for building AC. In fact, the omnipresent forestry culture creates high levels of collective interactions and cooperation (i.e., good social capital), assisted by the topographic profile of this region with many isolated valleys that facilitate a close relation between humans and forests. Local communities depend on forests, not only economically, but also for safety (e.g. limiting avalanches) and health (e.g. water purification). They seem to be well aware of the multiple benefits offered by the forests (i.e. good forest management and practices, Fig. 4e). This could explain the strong involvement of young people in the forestry sector (including in family businesses), which contrasts with the other studied FSES characterized by ageing populations. The functional networks of companies with active inter- sectorial institutions, combined with the substantial value-addition, contribute to maintaining the economic success of the region. For the moment, alpine forests do not suffer from the strong negative impacts of climate change due to their altitude. However, some pests such as beech canker and bark beetle are increasingly observed, thus creating more awareness of environmental change.

We observed that the pressure on wood resources has been recently increasing because of the installation of large industrial structures in the region. As a consequence, foresters must go to higher altitudes to find the necessary timber.

According to some respondents “There is a large demand for wood from new industries, but the forests are overharvested, and mountain harvesting encounters many difficulties here” (Forest operator ID42); “There are fewer and fewer small industries but more and more large companies, which increases economic pressure” (Sawmill company ID44).

This “altitudinal race” is limited by the technical constraints of lumbering. Thus, in order to maintain the status quo, regional companies end up importing wood from neighboring countries, instead of radically changing the regional economy. Despite seemingly exhibiting all the desirable requirements for local AC, we note that the alpine FSES is not prepared to make transformations, rather maintaining a “business as usual” approach.

Although transformation requires some crucial changes, these changes can be implemented by progressive compromises among stakeholders. We did not find any clear indication of what the alpine stakeholders will do in the face of the already evident wood shortages. An initial step could be to improve their transformability potential through restoring local cohesion, for which the alpine FSES has the necessary assets. For instance, local stakeholders could ensure the partial autonomy of their FSES from external economic actors through certain economic and governance compromises.

Local resources can be developed with progressive investments in forests to guarantee the availability of future resources, avoiding depending on imports. This compromise could be supported through public policies that change the way in which subsidies are granted by awarding more for resource production (e.g. plantations, forest management, private forest owners’ initiatives) and less for wood processing and harvesting. “Developing” these new forests could imply a social compromise on the desirable landscape characteristics through the possible introduction of new species from lower altitudes to ensure the sustainability of local resources.

Many of these compromises imply deceleration or even a reduction of economic growth, which may not be acceptable to some stakeholders if perceived as an injustice toward future generations.

Currently, it is not clear whether the alpine stakeholders are ready to prepare for the landscape transformation required to secure their timber sources. All indicators suggest that they have the capacity, but at the same time we observe their reluctance to act and a willingness to remain within their “comfort zone.”

Policy implications and recommendations Currently, stakeholders engaged in the forestry sector in the study FSES perceive the status quo as their primary adaptation option. This reflects overconfidence in their technical abilities to allow them to return to past states following potentially disruptive perturbations. However, global environmental change poses long-term and unpredictable pressures that render such robustness and resilience strategies of limited use due to the ever-changing context. In this uncertain and changing setting,

stakeholders must consider seriously the future conditions but also their current capacities to transform the respective FSES to anticipate possible changes. Table 2 summarizes this notion of compromise and a new vision of the forestry sector as a guide for relevant policymakers and practitioners.

For changing social-ecological systems with long life-cycles such as forests, the main recommendation for policy- and decision-makers is to promote and develop new forest values and landscapes. Nevertheless, practitioners must crucially develop, and above all, maintain diversity in FSES in terms of tree species/ages/genetics, forestry practices, production goals, and capitals, among others, possibly through evolution-oriented forestry (Lefèvre et al. 2014) (Table 2).

Conclusion

The observed preference of the different FSESs for adaptation coping strategies occurs through the maximization of one capital, leading to asymmetry in capital distribution while hampering other forms of capitals necessary for transformation opportunities. When all forms of capital are evenly developed, accepting decreased economic benefits and landscapes different from what was historically known could be the price to pay for the long-term adaptability of the system.

Although we conceptualized transformability as a continuity of resilience, the mechanisms and capitals required are not the same for both strategies. The development of transformative potential in social–ecological systems with long life cycles such as forests requires the accumulation of multiple, equivalent, and evenly developed capitals, but this also implies compromises. For us, a crucial step to develop transformability in FSESs is to encourage forestry stakeholders to change their mindset about forests and accept new paradigms. In the near future, stakeholders should reconsider the value of forests by integrating in their governance all the ecosystem services offered by forests and not only their biomass production in order to develop new social, political, and economic standards that do not necessarily exist in today’s practices and conceptions.

References

- Adger WN (2003) Social capital, collective action, and adaptation to climate change. *Econ Geogr* 79:387–404
- Aitken SN, Whitlock MC (2013) Assisted gene flow to facilitate local adaptation to climate change. *Annu Rev Ecol Evol Syst* 44:367–388. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1146/annurev-ecolsys-110512-135747>

- Anderies JM, Janssen MA, Ostrom E (2004) A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecol Soc* 9:1–28
- Anderies JM, Folke C, Walker B, Ostrom E (2013) Aligning key concepts for global change policy: robustness, resilience, and sustainability. *Ecol Soc* 18(2):8
- Arnould P, Marty P, Simon L (2002) Deux siècles d'aménagements forestiers: trois situations aux marges meridionales de la France. *Eria* 58:251–267
- Barthod C (1998) La multifonctionnalité des forêts entre discours et pratiques: illusion ou réalité à assumer? *Rev For Française*, numéro spécial annuel: 215–227
- Berdoulay V, Soubeyran O (2014) Adaptation, science de la durabilité et pensée planificatrice. *Nat Sci Sociétés* 22:114–123
- Bolte A, Ammer C, Löf M et al (2009) Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. *Scand J For Res* 24:473–482. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1080/02827580903418224>
- Bourdieu P (1986) The forms of capital. In: Richardson J (ed) *Handbook of theory and research for the sociology of education*. Greenwood, Westport, pp 241–258
- Boutefeu B, Arnould P (2006) Le métier de forestier: entre rationalité et sensibilité. *Environ Cult Société* 58(1):61–72
- Brang P, Spathelf P, Larsen JB et al (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* 87:492–503
- Cardinale BJ, Matulich KL, Hooper DU et al (2011) The functional role of producer diversity in ecosystems. *Am J Bot* 98:572–592. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.3732/ajb.1000364>
- Dedeurwaerdere T (2005) The contribution of network governance to sustainable development. *Les séminaires l'Iddri* 13:1–15
- Dupuis J, Knoepfel P (2013) The adaptation policy paradox: the implementation deficit of policies. *Ecol Soc* 18(4):31
- Evelya C, Fazey I, Pinard M, Lambin X (2008) The influence of philosophical perspectives in integrative research: a conservation case study in the cairngorms national park. *Ecol Soc* 13:52
- Fazey I, Fischer J (2009) Assisted colonization is a techno-fix. *Trends Ecol Evol* 24:475–476. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.tree.2009.05.003>
- Fazey I, Gamarra JGP, Fischer J et al (2010) Adaptation strategies for reducing vulnerability to future environmental change. *Front Ecol Environ* 8:414–422. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1890/080215>
- Fernandez-Manjarres J, Tschanz L (2010) Assisted colonization: protect managed forests. *Science* (80–) 330:1318

- Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. *Glob Environ Change* 16:253–267. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.gloenvcha.2006.04.002>
- Folke et al. (2002) Resilience and Sustainable Development: Building adaptive capacity in a world of transformations. Report from the Environmental Advisory Council, Ministry of Environment, Stockholm, Sweden
- Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social–ecological systems. *Annu Rev Environ Resour* 30:441–473. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1146/annurev.energy.30.050504.144511>
- Gaudin S, Madrolles F, Richard J-B, Brusten T (2016) How to take into account climate change in forest sites handbooks? *Rev Sci Tech Forêt Environ* 228:49–54
- Godard O (2010) Dossier « Adaptation aux changements climatiques » – Cette ambiguë adaptation au changement climatique. *Nat Sci Sociétés* 18:287–297. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1051/nss/2010036>
- Gomm R, Hammersley M, Foster P (2000) Case study method. Sage Publi, London
- Gupta J, Termeer K, Klostermann J et al (2010) The Adaptive Capacity Wheel a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. *Environ Sci Policy* 13:459–471
- Holling CS (1973) Resilience and stability of ecological systems. *Annu Rev Ecol Syst* 4:1–23
- Husson JP (2006) Vers des modèles forestiers plurifonctionnels. In: Galochet M (ed) *La forêt, Ressource et Patrimoine* (collectif). Ellipses Edition, Paris Institut National de l'Information Géographique et Forestière (2017) *Le mémento: inventaire forestier*
- Isbell F, Craven D, Connolly J et al (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526:574–577
- Jarzebski MP, Tumilba V, Yamamoto H (2016) Application of a tri-capital community resilience framework for assessing the social–ecological system sustainability of community-based forest management in the Philippines. *Sustain Sci* 11:307–320. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1007/s11625-015-0323-7>
- Karnkowski W, Sahajdak A (2010) Occurrence of the pinewood nematode in Portugal and Spain— threat for pine forests in Europe. *Progr Plant Prot* 50:1260–1264
- Lefèvre F, Boivin T, Bontemps A et al (2014) Considering evolutionary processes in adaptive forestry. *Ann For Sci* 71:723–739
- Liu J, Dietz T, Carpenter SR et al (2007) Complexity of coupled human and natural systems. *Science* 317:1513–1516. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1126/science.1144004>
- Loarie SR, Duffy PB, Hamilton H et al (2009) The velocity of climate change. *Nature* 462:1052–1055. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1038/nature08649>
- Maciver DC, Wheaton E (2005) Tomorrow's forest: adapting to a changing climate. *Clim Chang* 70(1):273–282

- Magnan A (2009) Proposition d'une trame de recherche pour appréhender la capacité d'adaptation au changement climatique. *Vertigo* 9(3)
- Magnan A (2014) De la vulnérabilité à l'adaptation au changement climatique: éléments de réflexion pour les sciences sociales. In: Monaco A, Prouzet P (dir.) *Risques côtiers et adaptations des sociétés*, ISTE Editions, pp 241–274
- McCarthy MA, Burgman MA (1995) Coping with uncertainty in forest wildlife planning. *For Ecol Manag* 74:23–36
- Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. *Ecol Appl* 17:2145–2151
- Mola-Yudego B, Arevalo J, Díaz-Yáñez O et al (2017) Wood biomass potentials for energy in northern Europe: forest or plantations? *Biomass Bioenerg* 106:95–103. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.biombioe.2017.08.021>
- Moon K, Blackman D (2014) A guide to understanding social science research for natural scientists. *Conserv Biol* 28:1167–1177. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1111/cobi.12326>
- National Forest Inventory (2011) A new ecological and forest parting of French territories: the Sylvo- Eco Region (SER). *L'Inventaire For* 1–8
- Nelson R, Brown PR, Darbas T, et al (2007) The potential to map the adaptive capacity of Australian land managers for NRM policy using ABS data. CSIRO, Australian Bureau of Agriculture and Resource Economics, prepared for the National Land and Water Resources Audit
- Nelson R, Kokic P, Crimp S et al (2010) The vulnerability of Australian rural communities to climate variability and change: Part II—integrating impacts with adaptive capacity. *Environ Sci Policy* 13:18–27. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.envsci.2009.09.007>
- Nunes da Silva M, Solla A, Sampedro L et al (2015) Susceptibility to the pinewood nematode of four pine species involved in potential range expansion across Europe. *Tree Physiol* 35:987–999
- Olsson P, Folke C, Hahn T (2004) Social– ecological transformation for ecosystem management: the development of adaptive co- management of a wetland landscape in southern Sweden. *Ecol Soc* 9(4):2
- Olsson P, Galaz V, Boonstra WJ (2014) Sustainability transformations: a resilience perspective. *Ecol Soc* 19(4):1
- Ostrom E (1990) *Governing the commons: the evolution of institutions for collective action*. Cambridge University Press, Cambridge
- Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. *Science* 325:419–422. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1126/science.1172133>

- Pahl-Wostl C (2009) A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Glob Environ Change* 19:354–365. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.gloenvcha.2009.06.001>
- Papillon P (2014) Les forêts périurbaines: des espaces récréatifs à la fonction prophylactique. Le cas des aires urbaines d'Alençon, de Blois et du Mans. Dodier R (Dir), Paris
- Percheval J (2014) Le développement de la filière bois-énergie en région Provence-Alpes-Côte-d'Azur. Report from the Regional Environmental Development and Housing Direction for the Ministry of Agriculture and Forest, Paris
- Pottier A (2014) Le massif forestier des Landes de Gascogne, un patrimoine naturel? Le regard des gestionnaires. *Ann Geogr* 698:1016–1038
- Ravera F, Tarrason D, Simelton E (2011) Envisioning adaptive strategies to change: participatory scenarios for agropastoral semiarid systems in Nicaragua. *Ecol Soc* 16:art20
- Schultz C (2008) Responding to scientific uncertainty in US forest policy. *Environ Sci Policy* 11:253–271
- Schultz L, Folke C, Österblom H, Olsson P (2015) Adaptive governance, ecosystem management, and natural capital. *Proc Natl Acad Sci* 112:7369–7374. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1073/pnas.1406493112>
- Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. *Glob Environ Change* 16:282–292. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.gloenvcha.2006.03.008>
- Szreter S, Woolcock M (2004) Health by association? Social capital, social theory, and the political economy of public health. *Int J Epidemiol* 33:650–667
- Thoening JC (1973) L'ère des technocrates, les cas des Ponts et Chaussées. Les Editions d'Organisation, Collection Sociologie des Organisations, Paris
- Thompson I, Mackey B, McNulty S, Mosseler A (2009) Forest Resilience, Biodiversity, and Climate Change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems, Montreal
- Tilman D, Reich PB, Knops JMH (2005) Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature* 441:629–632
- Tompkins EL, Adger WN (2004) Does adaptive management of natural resources enhance resilience to climate change? *Ecol Soc* 9(2):10
- Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social-ecological systems. *Ecol Soc* 9(2):5
- Walker B, Gunderson L, Kinzig A et al (2006) A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecol Soc* 11(1):13
- Wang T, Campbell EM, O'Neill GA, Aitken SN (2012) Projecting future distributions of ecosystem climate niches: uncertainties and management applications. *For Ecol Manage*

279:128–140. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.foreco.2012.05.034>

Williamson T, Hessel H, Johnston M (2012) Adaptive capacity deficits and adaptive capacity of economic systems in climate change vulnerability assessment. *For Policy Econ* 24:48–54. <https://doi-org.ezproxy.universite-paris-saclay.fr/10.1016/j.forpol.2012.09.006>

Wilson G (2010) Multifunctional “quality” and rural community resilience. *Trans Inst Br Geogr* 35:364–381

Acknowledgements

We are grateful for funding from the French National Research Agency (ANR), which provided support for the doctoral position of R. Sansilvestri through the AMTools French ANR project (ANR-11- AGRO-0005). We would also like to thank Laurent Simon for his helpful advice on natural capital issues. Finally, we would sincerely like to thank all the stakeholders who participated in the interviews and gave their time to the project.