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Forest temporal stability, a new tool to measure protected areas?

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Declaration

I, Robinson Vauthier, declare that this thesis is a result of my research investigations and findings. Sources of information other than my own have been acknowledged and a reference list has been appended. This work has not been previously submitted to any other university for award of any type of academic degree.

Signature: 

Date: 27/05/2021

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Abstract

Forests represent more than a third of France's territory, and one fourth of them are protected. Several types of protected areas exist in France to conserve these ecosystems. These protected areas have different organisations, with a governance scale ranging from local to international. However, there is no universal measure to estimate the long-term effect of protected areas on forest ecosystems. The present thesis attempts to establish the effect of protect areas on forest temporal stability during a period of 16 years over the mainland of France, using remote sensing data and the French national inventory. As a result, regional natural parks, Natura 2000 sites, and biosphere reserves influence positively the temporal stability of forests. Even though the superposition of protected areas can lead confusing results, the positive response of stability to different types of protected area suggest that it could be a suitable tool to be implemented in a broader assessment framework to evaluate protected areas outcomes.

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Introduction

Since the 18th century, 40% of the world's forest cover has been lost (Shvidenko et al., 2005). However, forest ecosystems account for more than half of the world biodiversity (Shvidenko et al., 2005) and the different ecosystem services they provide is estimated to worth $16.2 trillion per year (Costanza et al., 2014). Indeed, forest ecosystems provide different services, from global to local scale, by mitigating climate change through the absorption from or release of carbon in the atmosphere, by preventing land erosion, or by providing freshwater (Shvidenko et al., 2005). To protect these ecosystems and the services they provide, the totality or part of a forest can be designated as a protected area. The International Union for Conservation of Nature (IUCN) defines a protected area as "a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, Shadie, & Stolton, 2013, p. 8). From this definition, IUCN established seven types of protected areas that is possible to divide in two categories: inhabited protected areas and strongly protected area.

In France, forests represent 31% of the mainland territory, that being almost 170 000 km^2 (IGN, 2020). The particularity of French forest is its increased in size since the beginning of the 20th century because of rural exodus and agricultural revolution (Barbero, Bonin, Loisel, & Quézel, 1990; IGN, 2020). Forest protection in France started early with the establishment of the first protected area in 1861 with the *réserve artistique* of Fontainebleau (Ford, 2004). However, the first official national park was not established before 1963 (Office français de la biodiversité, 2021b), almost one century after the establishment of the national park of Yellowstone, USA, which is a ground scheme or inspiration for the organisation of many protected areas in the world (Adams, 2019; Adams & Hutton, 2007). At the present time, one fourth of French forests are classified as inhabited protected areas, but only 1.3% are strongly protected (OCDE, 2016) and in 2016, 50% of forests have a conservation state considered as inadequate (OCDE, 2016).

Many indicators can be used to measure the health of ecosystems or the outcome of protected areas (Blackman, 2013; Brooks, Wright, & Sheil, 2009). Indicator species and keystone species can be used to monitor an ecosystem, firstly because they represents ecosystem health accurately, and secondly because they are considered as the corner stone of an ecosystem (Lindenmayer, Margules, & Botkin, 2000; Simberloff, 1998). De Heer, Kapos, Miles, and Ten Brink (2004) proposed a "policy-relevant biodiversity index" based on number of species and population size to measure forests' state. However, Lindenmayer et al. (2000) highlighted that using a species or a group of species could lead to wrong assessment of ecosystem health because a single species could not sufficiently represent an ecosystem, and the difference of response between species facing a phenomenon could lead to wrong interpretation. At the forest scale, processes can be used such as the foliage deficit or the crown shape to measure forest's health (Office national des forêts, 2015; Zarnoch, Bechtold, & Stolte, 2004).

In addition to field-based measurements, remote sensing tools are becoming more popular since a few decades. They represent an opportunity for research as they are relatively low-priced, can collect data on a relatively long period, and easily accessible (Blackman, 2013). They allow the study of ecological phenomena occurring at large scale such as seasonal change in large resource supply (Polovina, Howell, Kobayashi, & Seki, 2001) or migration of large mammals (Burtenshaw et al., 2004). Different effects of forested areas have also been highlighted such as carbon storage or albedo effect (Bonan, 2008). Remote sensing can also help to grasp the extent of human impacts on the environment such as forest fire (Curt, Fréjaville, & Lahaye, 2016) or ocean pollution (Brekke & Solberg, 2005). They can also be used to measure outcomes of protected areas (Blackman, 2013; Joppa & Pfaff, 2011; Léonard, Witté, Rouveyrol, & Hérard, 2020).

Forest ecosystems can be characterised by diverse variables such as its age or its species composition (Madrigal-González, Herrero, Ruiz-Benito, & Zavala, 2017; Trumbore, Brando, & Hartmann, 2015). Among these variables, the temporal stability of forest can be defined as "the ability of a system to remain near an equilibrium point or to return to it after a disturbance" (Larsen, 1995, p. 86). Temporal stability represents the relation between the productivity of a forest and its variability over time (Isbell, Polley, & Wilsey, 2009), and an increase in productivity, a decrease of its variation, or both would result in a higher stability, synonymous of a "healthier" forest ecosystem. Biodiversity can influence temporal stability through different mechanisms: species asynchrony, the portfolio effect, and overyielding (Lehman & Tilman, 2000). The species asynchrony reduces the variation of productivity over time and the portfolio effect increases stability by statistical averaging due to a high number of species (Isbell et al., 2009; Tilman, 1999). The overyielding effect is the result of a higher productivity in mixture is higher than in monocultures (Jonsson, Bengtsson, Gamfeldt, Moen, & Snall, 2019; Jucker, Bouriaud, Avacaritei, & Coomes, 2014). These three mechanisms show that temporal stability is influenced by the interactions between the different organisms present in the ecosystem, but it can also be influenced by perturbations and forest management (Isbell et al., 2009; Jonsson et al., 2019; Larsen, 1995; Wales et al., 2020).

Forest temporal stability can be a functional biodiversity indicator following the classification of Noss (1990). It fulfils four out of seven criteria to be a biodiversity indicator established by Noss (1990): it is widely applicable, provides continuous assessment over a wide range of stress, easy and cost-effective, and relevant to ecologically significant phenomena. Moreover, in opposition with most indicators of sustainable forest management, temporal stability is time-sensitive (De Heer et al., 2004), allowing a relevant measure across years. For these reasons, forest temporal stability could be an indicator of the ecological state of forests and could estimate the role of protected areas in maintaining this state. To test this hypothesis, the "with-versus-without comparison" method proposed by Blackman (2013) will be applied on protected areas and non-protected areas in France and their effect on temporal stability will be compared, using the national forest inventory conducted by the National Institute of

Geographic and Forest Information (IGN, 2005), to test if French protected areas influence forest temporal stability. With this approach, it is expected that protected areas aiming to conserve forest ecosystems will influence temporal stability positively.

Protection of biodiversity in France

French forests have been under the power of the centralised State for a long time. Already in the second half of the 17th century, the king Louis XIV established an ordinance regulating the right of pasture and wood gathering by peasants in the entire country (Ford, 2004). The ordinance has later been used as inspiration to limit the use of forests that have been deteriorated during the French Revolution (Ford, 2004) and French administration heavily restricted the use of forests in order to restore them, leading to conflicts between the State and the population. During the 19th century, Parisian artists and bourgeoisie rose their voices to create the first protected area, a *réserve artistique* on the domain of Fontainebleau, to preserve the forest from a profit-oriented management (Ford, 2004). In this *réserve*, neither cutting nor planting by foresters were authorised along with the already implemented restrictions on forest use by the peasantry. Following the creation of this protected area, the first law to protect natural sites and monuments with an artistic feature was implemented in 1906 (loi du 21 avril 1906). Between 1921 and 1927, a succession of national parks and natural reserves were created in French colonies to protect natural areas from human intervention (Ford, 2004). However, they were not officially mentioned in French law before 1960 (loi n°60-708). By this law, the State took the complete responsibility for creating and managing national parks, with only a minor possibility of participation for the local communities.

Forty decades later, the national strategy for biodiversity (NSB), adopted in 2004, is the translation of the international Convention on Biological Diversity at the national scale (*Stratégie nationale pour la biodiversité 2011-2020*, 2012). The NSB aimed to involve all stakeholders from local to international levels and it proposes six strategical directions with 20 objectives to conserve, to restore, and to ensure a sustainable use of biodiversity (*Stratégie nationale pour la biodiversité 2011-2020*, 2012) A particularity of the NSB is its voluntary approach. It is a strategy proposed by the State to which any legal entity can decide to sign (*Stratégie nationale pour la biodiversité 2011-2020*, 2012). This voluntary approach shows a rupture with the traditional top-down approach of the French State, and it aims to enhance the commitment of stakeholders. As a result, in 2015, most French regions had created their own regional biodiversity strategies (Moral, Clap, Ritossa, & Moncorps, 2016).

The law for the reconquest of biodiversity, nature, and landscapes (loi n°2016-1087) adopted in 2016 is the continuity of two environmental laws: the law regarding the protection of nature (loi n°76-629) adopted in 1976 and the law regarding the protection and improvement of landscapes (loi n°93-24) adopted in 1993 (Ministère de la Transition écologique, 2017). This law aims to reinforce the protection of the environment by instituting a reparation scheme for environmental damages, a principle of nondecline for the protection of the environment, and a principle of ecological solidarity between territories (Ministère de la Transition écologique, 2017). It also aspires to accentuate ecological knowledge and its sharing (Ministère de la Transition écologique, 2017). In 2018, France adopted its biodiversity plan (BP) to accelerate the execution of the NSB and to facilitate the execution of the law for the reconquest of biodiversity, nature, and landscapes (Ministère de la Transition écologique, 2021a). The BP is divided in six axes, with 24 objectives such as preventing land artificialisation, the creation of new protected areas, fortify French environmental laws, and establish a European and international road map for biodiversity protection (Ministère de la Transition écologique, 2021a).

In 2010, France adopted its national strategy for protected areas until 2020, and recently extended to 2030. This strategy, similarly to the NSB, have several objectives: 30% of the territory should be protected by 2030, with 10% under stronger protection regulations, reinforce regulations tools, a better monitoring of activities within protected areas, or improve international cooperation (Ministère de la Transition écologique, Ministère de la mer, & biodiversité, 2021; Office français de la biodiversité, 2021a). To achieve the different objectives, the State relies on a cooperation of actors at different levels, from local to national. France also recognised the importance of international cooperation by ratifying international convention such as the Convention on Biological Diversity (Moral et al., 2016), the Ramsar Convention, or establishing internationally recognised biosphere reserves, but also by mentioning international coordination as a key tool in its NBS (Moral et al., 2016). France had also an important role in the creation of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and IUCN (OCDE, 2016). Following the process of power decentralisation established by the French state (Jamet, 2007), local authorities can participate in decentralised cooperation with foreign agencies to exchange knowledge and practices (Moral et al., 2016). This decentralised cooperation is an important tool to reach international goals of conservation, as biodiversity is a continuum in space that is not stopped by borders.

A characteristic of France is the centrality of the State in the organisation, regulation and negotiation between institutions and stakeholders (Jamet, 2007; Parra, 2010), but also the power given to lower-scale administrations such as the regions and the departments (Parra, 2010). The long French tradition of centralised power and top-down approach was at its peak during the 30 years of post-war economic growth, the *Trentes Glorieuses* from 1945 to 1973, characterised by an intensive urbanisation coordinated by the State (Parra, 2010). In the 1960s, the regions and their regional prefects were created to represent the State at a regional scale (Parra, 2010). Regions assembles several departments, smaller administrative parts, and can be considered as a first step of the decentralisation of the State, with a transfer of administrative competence to a local scale (Parra, 2010).

In 2006, a greater capacity is given to regional, departmental, and municipal administrative power with an environmental law regarding national parks and regional natural parks (loi n°2016-1087). This law allows a delimitation of national parks made by consultation with local stakeholders, and not only decided by the State. France possesses several institutional bodies in charge of the environment. With the environmental law of 2016, a new centralised agency was created, the *Agence française pour la biodiversité* (Ministère de la Transition écologique, 2017), later modified to become the *Office français de la biodiversité* (OFB). The OFB is in charge of the coordination of activities in national parks, marine protected areas aquatic environment, and green spaces (Ministère de la Transition écologique, 2017). In addition to the OFB, the *directions regionals de l'environnment, de l'aménagement et du loge* (DREAL), grouping since 2009 other local agencies, are the representation of the Ministry of Environment at the regional level (OCDE, 2016).

French protected areas

France defines protected areas, based on the IUCN definition, as "a geographical space clearly defined, recognised, dedicated, and managed, with all effective means, juridical or else, to ensure long-term conservation of nature, together with the ecosystem services and cultural values associated with it" (Ministère de la Transition écologique et al., 2021). Among protected areas, it is possible to distinguish strong protection zones "in which pressures produced by human activities most likely to compromise the ecological stakes of this zone are suppressed or strongly restricted, in a lasting way, by the implementation of property protection or adapted regulation, associated with an effective control of the activity" (Ministère de la Transition écologique et al., 2021).

From these two definitions, it is possible to distinguish four ways to establish a protected area (Léonard, Rouveyrol, Grech, Chanet, & Hérard, 2018). A protected area can be established by contractual protection or international convention. Through contractual protection, activities in an area are regulated by established contracts or charters between the State and landowners. International conventions certify an area following criteria specific to each program. The strong protection zones can be established by either regulative protections or property control. Regulative protections allow the implementation of regulations to protect natural and cultural heritage on a land that is not a State property. Property control is the acquisition of land by the State, allowing a direct management of the land by the State.

Biotope protection orders

Biotope protection orders (*arrêtés préfectoraux de protection des biotopes*, APBs) have been implemented in 1997 (Ministère de la Transition écologique, 2020) and are numbered 948 in 2021 (Figure 1), covering more than 1 750 km^2 (0.32%) of Metropolitan France (Muséum national d'Histoire naturelle [Ed], 2003-2021). APBs have the advantage to be fast and easy to implement, and an average of 23 APBs is declared per year (Léonard et al., 2018). They are applied to prevent the "destruction, alteration, or degradation" of significant habitats for species "with scientific interest, essential role for

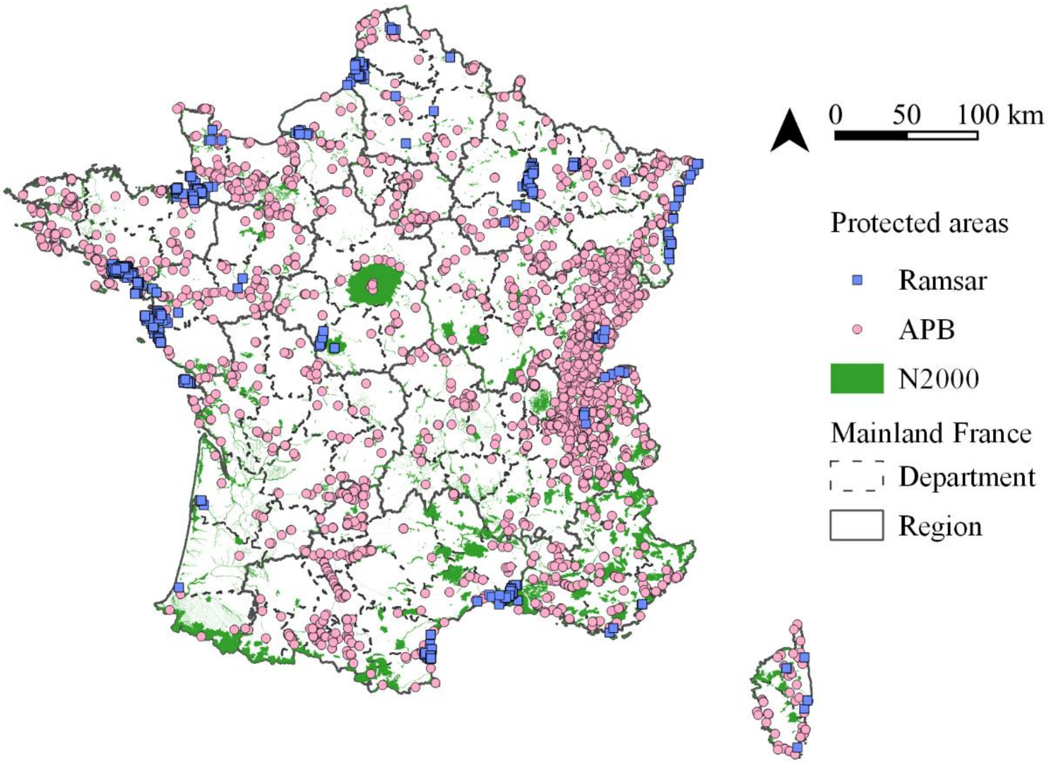

Figure 1. Location of Ramsar sites (Ramsar, n = 38), biotope protection order (APBs, n = 948), and Natura 2000 sites (N2000, n = 1755) on mainland France territory. Marine areas are not display on the map because of the scope of the analysis on forest.

the ecosystem, or considered as natural heritage" (Art. L411-1, Code de l'environnement). APBs are a tool that can be used at the local scale to protect the environment. Indeed in opposition with numerous types of protected area, their implementation does not require the intervention of the Minister dedicated to the environment, but only the intervention of the departmental prefect (Ministère de la Transition écologique, 2020). However, APBs can solely prohibit or regulate activities within the designated areas, and management or restauration plans cannot be established (Ministère de la Transition écologique, 2020).

The procedure to establish an APB can emerge from a private individual or a public agency. Next, investigations are conducted by public institutions to identify scientific interests of the APB and pressures encountered in the area. Simultaneously, the future orders to regulate or to prohibit activities are drafted. Then, a mandatory local consultation of concerned municipalities, the regional scientific council (CSRPN), and the departmental commission of nature, landscapes, and sites (CDNPS). Other actors such as private stakeholders or other public institutions can be optionally included in the consultation. The final step to implement an APB is its signature by the prefect. Once an APB has been established, no legislative tool obliges to monitor its state (Ministère de la Transition écologique, 2020) but a monitoring committee can be introduced. However, such a committee is often not instituted (Léonard et al., 2018). The compliance with APB's regulations and interdictions is often controlled by agents from the OFB or other environmental agencies (Léonard et al., 2018). In the case of a breach of the regulations imposed by the APB, fines and prison sentences can be applied as stipulated by the articles L415-3 and R415-1 (Code de l'environnement).

APBs are rarely revoked. When it is the case, it is often to reshape the site concerned by the APB in a bigger area, or to replace the APB by a legally stronger tool to protect the area such as national park (Léonard et al., 2018). However, numerous stakeholders from public institutions esteem that a revision or repeal of most APBs is needed (Léonard et al., 2018). A revision would be necessary to estimate again the APB's area and the species present within, to update the regulation concerning the activities in the area, and to update the stakeholders involved in the APB. In some case, a repeal of APB is required because the biotope on focus disappeared (from natural causes or not), the APB can have a lack of utility, or can be overlay by a stronger legislative tool, e.g., national park or regional natural park.

Regional natural parks

Regional natural parks (*parcs naturels régionaux*, RNPs) were created to protect and to highlight rural inhabited spaces with an important natural and cultural heritage, and a "fragile state" (Fédération des Parcs Naturels Régionaux de France, 2021; Lefebvre & Moncorps, 2010). RNPs were established for the first time in 1967 by governmental decree, with a "desire to convince instead of constrain" (Fédération des Parcs Naturels Régionaux de France, 2021), meaning that RNPs are meant to be the result of a cooperation between municipalities, local stakeholders, and the State. RNPs have also been created to buffer the socio-economic loss due to an important post-war rural exodus by creating a touristic area economically attractive (Lajarge, 1997; Parra, 2010). In 2021, there are 54 RPNs (Figure 2) in the Metropolitan France with a total of 91 203.11 km^2, covering 16.63% of the mainland (Muséum national d'Histoire naturelle [Ed], 2003-2021). Officially, RNPs have five objectives: protection of the environment, spatial planning, economic and social development, and education and formation of the population (Art. L333-1, Code de l'environnement). Therefore, RNPs are a place for research, experimentation, and innovation to preserve natural and cultural heritage, and encourage a sustainable development (Art. L333-1, Code de l'environnement; Streib, 2019).

The creation of RNPs emerges from local desire, with a proposition coming from municipalities that create a charter that settle the objectives and delimitations of the park for 10 years (Art. L333-1, Code de l'environnement; Parra, 2010). This charter is a contract made between the different stakeholders that should be involved in the RNP management. Discussions between these actors allow to establish the delimitation of the park, but also common objectives that should be attain at the end of the 10-years period (Lajarge, 1997). The charter must be approved by decree from the Council of State

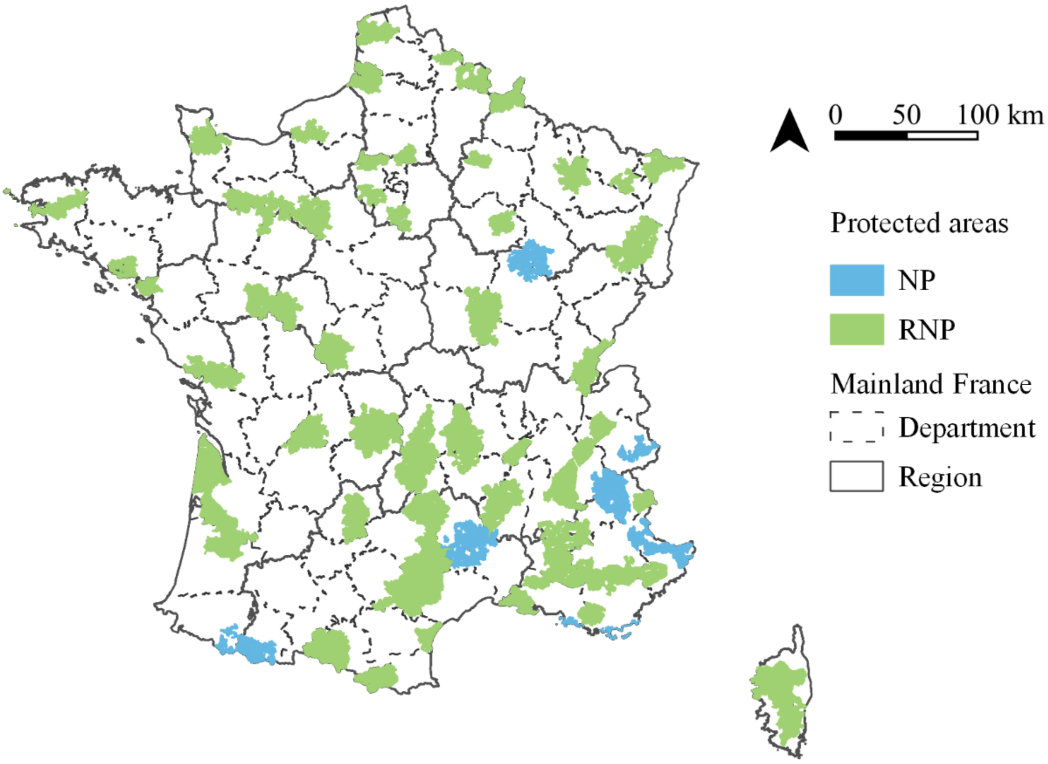

Figure 2. Location of the national parks (NPs, n = 8) and regional natural parks (RNPs, n = 54) on mainland France territory. Marine areas are not display on the map because of the scope of the analysis on forest.

(Art. L333-1, Code de l'environnement) and will be revaluated at this end of this period (Lajarge, 1997). If an RNP does not reach its objectives before the revaluation of its charter, the area can lose its designation of RNP. For instance, the *Marais poitevin* lost the RNP designation in 1996, before getting it back in 2014 (Pernet, 2019).

RNPs are managed by mixed unions (*syndicats mixtes)*. Each mixed union groups all municipalities that approved the charter established when the RNP was created (Streib, 2019), but also representatives of the region(s) the park lies in. The mixed union often includes representatives from the department(s) and from the major socio-professional categories (Fédération des Parcs Naturels Régionaux de France, 2021). RNPs are mainly financed by the municipalities and the ministry responsible of the environment (Fédération des Parcs Naturels Régionaux de France, 2021) with an average funding of €2.8 million per RNP (Salanié & Coisnon, 2016). However, other funding can be provided by other ministries and the European Union through projects (Fédération des Parcs Naturels Régionaux de France, 2021).

National parks

The first French national park (NP) was established in 1963. In 2021, there are eight NPs present on the mainland (Figure 2) (Office français de la biodiversité, 2021b) with a total area of 11 812.60 km^2 (1.07% of the territory) (Muséum national d'Histoire naturelle [Ed], 2003-2021). NPs are defined by the

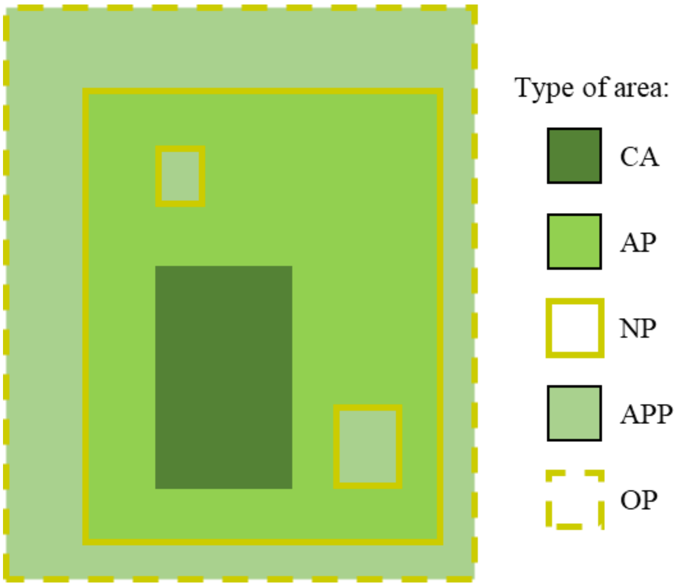

Figure 3. Simplified organisation of a national park. The core area (CA) and the area of partnership (AP) form the national park (NP). The NP and the area of potential partnership (APP) form the optimal perimeter (OP) of a national park. Modified from Office français de la biodiversité (2021b).

law L331-1 (Code de l'environnement) as terrestrial or maritime areas with a natural environment, and cultural heritage, with special interests. The same law article highlights the importance to preserve NPs, and to prevent alterations of their diversity, composition, aspect, and evolution. NPs have also a role of nature preservation, and unlike APBs, a role of nature restoration when necessary (Art. L331-9, Code de l'environnement).

NPs are organised in two different zones (Figure 3): a core area lying within an area of partnership both linked by a principle of ecological solidarity translated by a harmonisation of actions between both areas (Amara, 2008; Office français de la biodiversité, 2021b). The core area has stricter regulations and the goal to preserve the natural and cultural heritage. The authority of NPs within this area is hardly contestable and restoration actions undertake by NPs cannot be opposed by land users and/or owners (Art. L331-9, Code de l'environnement). The delimitations of the core area are defined before the establishment of a national park. The area of partnership is more flexible as its perimeter is defined by the adherence of municipalities to the park's charter. However, not every municipality can join the area of partnership. These municipalities must be within the optimal perimeter of the NP set by the State's decree establishing the NP. If a municipality decides to do not ratify the charter, it remains in an area of potential partnership, and have a period of three years after the charter has been approved to join the area of partnership.

The management of NPs is proceeded by a public institution under the administrative supervision of the ministry in charge of the environment (Office français de la biodiversité, 2021b). NPs also have the obligation to follow a charter valid for 15 years and established by NP's representatives, municipalities, and local stakeholders (Office français de la biodiversité, 2021b). The charter defines the perimeter of the NP, protection objectives for the core area, and the orientation of protection and sustainable development for the area of partnership (Art. L331-3, Code de l'environnement). Both the charter and the public institution managing the NP need to be officially accepted through a decree signed by the Council of State (Art. L331-2, Code de l'environnement). The establishment of a NP can take time as its delimitations, regulations, and prohibitions, have impacts on the social and economic life of the area. For instance, the *Parc national des Calanques* in South-eastern France was established after 15 years of negotiation (Cadoret, 2017) and the reform of the *Parc national des Pyrénées* in 2008 led to contestations against a possible reduction of economic and cultural activities by locals (Clarimont, 2013).

Despite an important local steering power, NPs stay under the control of the State, from which they originate (Parra, 2010). The public institution of a NP is attached to the OFB (Art. L331-8-1, Code de l'environnement) and is led by a director appointed by the Minister (BDRH conseils, Parc nationaux de France, & L'atelier technique des espaces naturels, 2011). NPs also have a board of directors consisting of State representatives, regional government representatives, one representative of the NP, and members chosen for their expertise in certain domains such as biologists or economists, with a total amount of members specific to each park (Art. L331-8, Code de l'environnement). NPs received their funding from the State, and potentially from regional governments (Art. L331-11, Code de l'environnement).

Most activities in the core area are prohibited unless they are recognised as compatible with the park's objectives (Amara, 2008). Activities in the core area should not deteriorate the natural or cultural heritage by any means (Amara, 2008). Activities that can be maintained are often related to cultural heritage such as traditional agricultural, forest, or pastoral practices (Clarimont, 2013). To maintain these activities, NPs can proceed to the restoration the necessary infrastructure such as refuges in the *Parc national des Pyrénées* (Clarimont, 2013). In the area of partnership, activities are authorised in the extent that they do not negatively impact the core area, and they are in favour of an economic, ecological, and social sustainable development (Amara, 2008). The type of activities in NPs can be various, but many focus on the tourism sector with development of accommodation, hiking trials, or skiing areas (Clarimont, 2013). In case of violation of the different regulations in a NP, fines that can reach €75 000 and prison sentences of maximum two years can be applies (Art. L331-26, Code de l'environnement).

Natura 2000 sites

Following the Rio Summit in 1992, the European Union created a network of protected areas to obstruct the biodiversity loss it was facing, the Natura 2000 network (Ministère de la Transition écologique, 2019). The Natura 2000 network has two goals: preservation of biodiversity and cultural heritage, and the consideration of economic, social, and cultural demands (Ministère de la Transition écologique, 2019). Natura 2000 sites also aim to preserve threatened species (Ministère de la Transition écologique, 2019), and to restore their habitats when it is needed (Allag Dhuisme et al., 2015). After years of conflicts between the State and the European Union, and conflicts between the State and local stakeholders, France initiated the creation of Natura 2000 sites in 2000 (Alphandery & Fortier, 2001; McCauley, 2008). In 2020, France numbers 1 755 Natura 2000 sites (Figure 1), covering 70 986.69 km^2

(12.93%) of the mainland (Muséum national d'Histoire naturelle [Ed], 2003-2021). The main habitats composing these sites are forests (43%), meadow and moor (29%) and agricultural land (20%) (Ministère de la Transition écologique, 2019).

Natura 2000 is based on two European directives, the Birds Directive and the Habitats Directive, respectively adopted in 1979 and 1992 (Ministère de la Transition écologique, 2019). These two directives enable the establishment of two distinct types of Natura 2000 sites: Special Protection Areas (SPAs) and Special Area of Conservations (SACs) (Ministère de la Transition écologique, 2019). SACs, are based on *zones naturelles d'intérêt écologique, faunistique et floristique* (ZNIEFF) (Ministère de la Transition écologique, 2019). ZNIEFFs are built on flora and fauna inventories covering the entire territory and indicate zones with a particular ecological interest. SPAs are based on bird inventories conducted by the *Ligue pour la protection des oiseaux* since the 1980s (Ministère de la Transition écologique, 2019). After a SAC or SPA have been identify, the departmental prefect suggests the potential Natura 2000 sites to the municipalities that would be involved in their establishment, and after approval the propositions are sent to the ministry in charge of the environment, then to the European Commission, and finally approved as Natura 2000 sites (Art. L414-1, R414-3, & R414-4, Code de l'environnement; Ministère de la Transition écologique, 2019).

Natura 2000 sites are managed by a steering committee named *comité de pilotage* (COPIL), appointed by the departmental prefect (*Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019), and composed by local stakeholders and State representatives (Ministère de la Transition écologique, 2019). A particularity of the COPIL is that the number and type of stakeholders included in the committee is dependent on each site particularity, and State representatives have only a consultative role on the board (*Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019). In the case the majority of a Natura 2000 site falls in the perimeter of a national park, the public institution in charge of the NP is also in charge of the Natura 2000 site and its management through the NP's charter (*Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019).

The management of Natura 2000 sites relies on management plans, the *documents d'objectifs* (DOCOBs) produced by the COPIL, validated by the departmental prefect (Art. L414-2 & R414-8-1, Code de l'environnement; *Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019; Ministère de la Transition écologique, 2019). Even though a DOCOB should be established for each site, in 2015 only 85% of Natura 2000 sites have submitted a complete DOCOB (Allag Dhuisme et al., 2015). The DOCOB contains many information such as description of the site, conservation and restoration objectives, the sustainable development goals to reach, suggestions to reach them, and contracts and charters established to reach these objectives (Art. L414-1, Code de l'environnement). Because of the information it contains, the management plan should be updated regularly but no revaluation date is officially set up (*Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019). Activities on Natura 2000 sites are not prohibited unless they contribute to the deterioration of a habitat or a species (Art. L414-1, Code de l'environnement). However, any activities or construction projects need their impacts on the site to be assessed (Art. L414-4, Code de l'environnement).

France, because of the turbulent history of Natura 2000 implementation on its territory, opted for a contractual management of the sites (Alphandery & Fortier, 2001). Agreements are made between COPILs and landowners, either as contracts or charters. The contracts, called Natura 2000 contracts, are signed in order to achieve the restoration of a habitat, or the conservation of a species, in exchange of monetary compensation by the State (Art. L414-3, Code de l'environnement). There are three types of Natura 2000 contracts: agricultural contracts, forest contracts, and neither farming nor forest contracts (Allag Dhuisme et al., 2015). The Natura 2000 charter is similar to the Natura 2000 contract, but based on voluntary work (*Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres*, 2019). Between 2007 and 2013, 80% of the French Natura 2000 budget was allocated to the Natura 2000 contracts (Allag Dhuisme et al., 2015).

Ramsar sites

Ramsar sites have the primary goal to protect wetlands. They have been established following the international Ramsar Convention signed in 1971 by France, grouping 170 countries to this day (Ministère de la Transition écologique, 2021b). Originally created to protect water birds and their habitat, Ramsar sites now aim to protect wetlands for their ecological and cultural values. A sustainable use of wetland is also stated in French legislation (Art. L336-2, Code de l'environnement). Even though, there is no legislation on how to manage a Ramsar site, all signatory countries meet every three years to evaluate actions of the past years and to plan the actions for the next three years (Ministère de la Transition écologique, 2021b), assuring a regular monitoring of progress on these sites.

In France, 38 sites (Figure 1) have been established in the mainland since 1986, date of ratification, representing 7 970.43 km^2 (1.45%) of the territory (Muséum national d'Histoire naturelle [Ed], 2003-2021). A majority of these sites were created on existing protected areas, with a majority covered by Natura 2000 sites and RNPs due to the procedure to establish a Ramsar site (Alcoulombre, 2016). Indeed, a governmental notification of December 2009 specifies the steps to create a Ramsar site (Direction de l'eau et de la biodiversité, 2010). To be established as a Ramsar site, an area must first fit criteria to be define as a wetland site of international importance (WSII). From the WSIIs designated, the ones already subject to protection measured will be prioritised to apply for the Ramsar appellation. Once the Convention’s Secretariat validated the WSII as a Ramsar site, it needs to be accordingly managed.

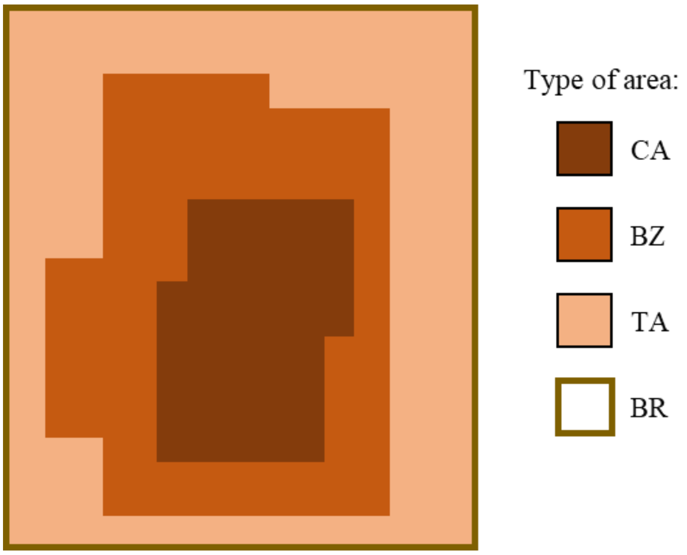

Figure 4. Simplified organisation of a biosphere reserve. The core area (CA) is the strict conservation area, the buffer zone (BZ) allows activities compatible with the CA, and the transition area (TA) circles the BR and foster sustainable development. The three zones form the biosphere reserve (BR). Modified from UNESCO (2019).

Ramsar sites must have a monitoring committee, a steering committee, and a management plan (Alcoulombre, 2016). The notification from 2009 recommends to do not create additional management body, therefore 80% of Ramsar sites' management rely on the already existing institutions of the sites there are superposed to, with corresponding steering committees and management plans (Alcoulombre, 2016). However, if the Ramsar site is larger or smaller than the protected area it is superposed to, the management plan should be created. It needs to be updated every six years and must contain a description of the site, the conservation objectives (Direction de l'eau et de la biodiversité, 2010).

Biosphere reserves

Biosphere reserves (BRs) are part of the international Man and the Biosphere Programme (MAB) started in 1971 by UNESCO (UNESCO, 2019). Their creation resulted from the Convening of the Intergovernmental Biosphere Conference in 1968 and growing concerns for the environment and resource preservation (Lefebvre & Moncorps, 2010). BRs are nominated by national governments, selected by the MAB International Coordination Council, and remain under the authority of state they are located in (UNESCO, 2019). To be established, BRs need to be based on nationally recognised protected areas. Therefore, most French BRs are based, at least partially, on regional natural parks or national parks (Lefebvre & Moncorps, 2010). After the adoption of the Seville Strategy for Biosphere reserves in 1996, BRs were assigned three main functions: conservation of biodiversity, development of a sustainable economy, and logistic support for research and education (Bouamrane et al., 2016; UNESCO, 2019). With the three objectives, BRs emphasise on community-based conservation and preservation of human activities that shaped the environment to be conserved (Bouamrane et al., 2016). BRs have also a common spatial organisation with three distinct areas (Figure 4) (UNESCO, 2019). The inner part of the BR is named the core area and correspond to a strictly protected area. The buffer zone surrounds the core area. Activities in this area oriented toward research, education, and monitoring of the ecosystem. The outer area is the transition area, where communities foster an economic, social, and environmentally sustainable development.

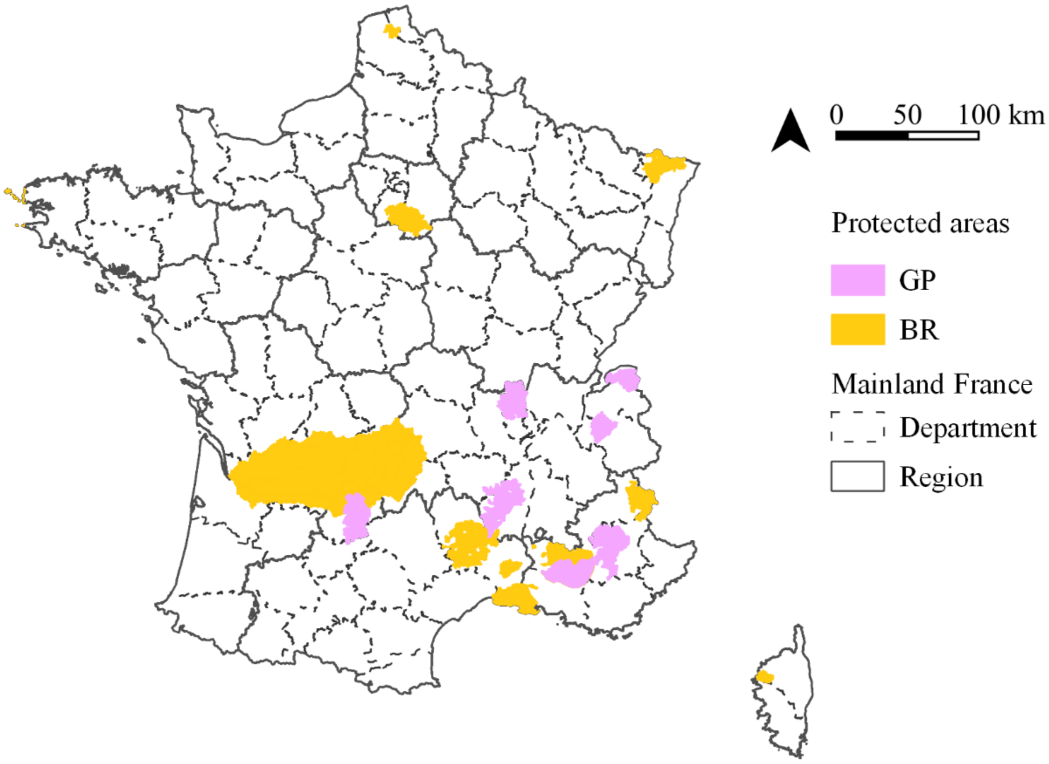

Figure 5. Location of geoparks (GPs, n = 7) and biosphere reserves (BRs, n = 12) on Mainland France territory.

France established its first BR in 1977 and today, a total of 12 BRs are present in France (Figure 5) (Mathevet, Cibien, & Atramentowicz, 2020). They cover 6.89% of the territory, with a total of 37 786.21 km^2 (Muséum national d'Histoire naturelle [Ed], 2003-2021). French BRs do not have a legal status (Lefebvre & Moncorps, 2010). This absence of status is a choice to avoid an overload of legislative text on protection and conservation of the environment (Comba, 2011), and more flexibility in the management of BRs (Lefebvre & Moncorps, 2010). The majority of BRs is managed by public institutions: regional natural parks, national parks, or mixed unions (Mathevet et al., 2020). Activities in BRs are various. Most BRs have biodiversity monitoring programs, and even though research projects are numerous, they are mainly located in BRs where a research centre is located near of within a BR (Mathevet et al., 2020).

Geoparks

Geoparks (GPs), similarly to the biosphere reserves, are entities endorsed by UNESCO but remain under the sovereignty of the government of the country they are located in (Farsani, Coelho, & Costa, 2011; UNESCO, 2017). They are “single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education and sustainable development” (UNESCO, 2017). However, not only geological features are considered to create a GP, but also the ecological, archaeological, or cultural value of the site (Farsani et al., 2011). In opposition with the biosphere reserves, the establishment of GPs emerges from a will of local communities to protect geological heritage (Mc Keever & Zouros, 2005; UNESCO, 2017). In 2000, four European territories with noteworthy geological features in France, Germany, Greece, and Spain, created the European Geoparks Network, later join by other territories from other European countries. In 2001, the European Geoparks Network signed a collaboration agreement with UNESCO to become the Global Geopark Network, allowing an expansion of the network outside the borders of Europe (Mc Keever & Zouros, 2005).

France have established 7 GPs since 2000 (Mc Keever & Zouros, 2005; UNESCO, 2017) on 2.11% (11 561.63 km^2) of the territory (fig. 5) (Muséum national d'Histoire naturelle [Ed], 2003-2021). Their management is community-based, with the involvement of local governments, economic stakeholders, educational actors (UNESCO, 2017). GP must also have a management plan approved by all collaborators setting the objectives they need to reach (UNESCO, 2017). However, like biosphere reserves, GPs have no legal status in France. Hence, the management of a park is not delegate to a specific committee, and RNP's mixed unions are the administrators of more than half GPs (Muséum national d'Histoire naturelle [Ed], 2003-2021). GPs are also integrated in the Global Geopark Network, with important cooperation with one another through exchange of ideas, coordination meetings, and common projects (Farsani et al., 2011).

Methods

The National Forest Inventory

The study area spreads on the entire national territory of France, with the exception of overseas territories. The National Institute of Geographic and Forest Information (IGN) carries a yearly inventory campaign of French forests (IGN, 2005), with a total of 5 378 plots sampled in 2018. In this inventory, a forest is considered as an area of minimum 0.005 km^2, with a forest cover of minimum 10% and 20 m width (IGN, 2020). Each plot sampled has a diameter of 25 m. For each plot, the soil cover (SC), the plantation type (PT), and the vertical structure of the forest stand have been described. The type of land use (LU), the presence of management marks for commercial purpose (MM), the type of incident (IT) the plot could have suffer in the past, and the skidding distance (off-road timber transportation, SD) have also been characterised (Table 1).

Several ecological characteristics were measured on 5 087 plots out of the total number of plots. At individual level, the height and the circumference of tree were measured during the inventory. At the plot level, the total basal area (BA, m^2) of trees per plot was calculated as $BA = \sum_{i=1}^{n} \pi \times \left(\frac{c_i}{2\pi}\right)^2$ (Wheater, Beel, & Cook, 2011), where c_i is the circumference of the tree i on the plot. The number of tree species present (SP_{Ric}) on each plot was censused. Maximum height and circumference of trees were

Table 1. Categorical variables used for the analysis with their abbreviation and definition.

Variables	*Parameter level*	*Definition*
Soil cover (SC)	SC_1	Closed woodland
	SC_2	Spinney
	SC_3	Open woodland
Land use (LU)	LU_0	No usage
	LU_A	Farming
	LU_F	Fire-break
	LU_G	Hunting
	LU_L	Network for wood production
	LU_M	Military ground
	LU_R	Protected area
	LU_T	Leisure
Management mark (MM)	MM_0	No trace
	MM_1	Light management traces
	MM_2	Evident management traces
Incident type (IT)	IT_0	No incident
	IT_1	Fire
	IT_2	Mortality
	IT_3	Slump, landslide, flood
	IT_4	Storm
	IT_5	Other
Plantation type (PT)	PT_0	No plantation
	PT_P	Regular plantation with visible mesh
	PT_Q	Regular plantation without visible mesh
	PT_X	Other plantation type
Skidding distance (SD)	SD_0	< 200 m
	SD_1	200-500 m
	SD_2	500-1000 m
	SD_3	1000-2000 m
	SD_4	> 2000 m
Presence in protected area (PAP)	PAP_0	Plot outside any protected area
	PAP_1	Plot within any protected area
Type of protected area (PAT)	PAT_{None}	Plot outside any protected area
	PAT_{APB}	Plot within APB
	PAT_{BR}	Plot within BR
	PAT_{GP}	Plot within GP
	PAT_{N2000}	Plot on Natura 2000 site
	PAT_{NP}	Plot within NP
	PAT_{RNP}	Plot within RNP
	PAT_{RS}	Plot on Ramsar site
	PAT_{Mixte}	Plot within at least two protected area types

averaged per plot using the community weighted mean method in order to take to account the interindividual variability (Lepš, de Bello, Šmilauer, & Doležal, 2011), as $T = \sum_{i=1}^{n} p_i \times t_i$ where T is the community weighted mean of the trait, p_i is the percentage of the total basal area represented by the tree i at the plot-level, and t_i is the trait value of the tree i at the plot-level. With this method, the mean maximum tree height (H_{max}, m) and mean tree circumference (C_{μ}, cm) were calculated for each plot. From these 5 087 plots, only 5 010 were defined as eligible to the inventory by the IGN and were used for the analysis.

Stability

The Normalised Difference Vegetation Index (NDVI) was used as a proxy for the aboveground biomass productivity at each plot of the study, as Wang, Rich, Price, and Kettle (2004) showed a strong correlation between wood production and NDVI. NDVI is calculated as $NDVI = \frac{NIR-Red}{NIR+Red}$ where NIR stands for near-infrared radiations (0.7 – 1.1 μm) and Red is the red visible wavelength of the light spectrum (0.6 – 0.7 μm), and it is a measurement related to vegetation photosynthetic rates as leaves of green plants absorb red radiations and reflect NIR (Didan, Barreto Munoz, Solano, & Huete, 2015; Wang et al., 2004). Therefore, NDVI is dependent on the type and state of the vegetation. NDVI values were retrieved from the MOD13Q1 product from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite from the NASA (Didan, 2015). This product generates NDVI layers every 16 days, with a total of 23 images per year with a resolution of 250 × 250 m. Even if there is a spatial mismatch between the plot size (diameter of 25 m) and MODIS pictures (250 × 250 m), Garcia-Palacios, Gross, Gaitan, and Maestre (2018) showed a closed relationship between both sources of data, allowing to use MODIS pictures to estimates the productivity of inventory plots.

NDVI values from May to September of each year (10 values) were used to calculate the annual NDVI as the average NDVI per year during the period 2000-2016. The period of May to September was chosen to capture the growing season of all trees. The annual NDVI was used to measure the temporal stability of each plot as $S = \mu \times \sigma$ where S is the temporal stability of the plot, μ is the mean annual NDVI and σ its standard deviation, following the method by Garcia-Palacios et al. (2018). If stability value is near 0, it transcribes an ecosystem with large variation in comparison to its mean productivity, indicating disturbances in the ecosystem (Lehman & Tilman, 2000). From the 5 010 plots eligible for the inventory, 1 126 plots had at least one missing NDVI picture between May and September of one of the years between 2000 and 2016. These plots were discarded from the analysis and the remanent 4 157 plots were used for the statistical analysis.

Protected areas

The delimitations of the different types of protected area in France have been retrieved from the National Inventory of Natural Heritage (Muséum national d'Histoire naturelle [Ed], 2003-2021). These protected areas included biotope protection orders, geotope protection order, natural habitat protection order, biosphere reserves, natural or mixed sites from the World Heritage List by UNESCO, sites established by the coastal protection agency, geoparks, Natura 2000 sites, national parks, regional natural parks, Ramsar sites, biological reserves, national game reserves, national natural reserves, and regional natural reserves. The presence or absence of each of the 4 157 plots within the different protected areas have been determined using the software QGIS (QGIS.org, 2021). If less than 30 plots were within a protected area type, this protected area type was discarded from the analysis. Note than for this selection, a plot can be simultaneously within several protected areas. For further analysis, biotope protection orders (APBs), biosphere reserves (BRs), geoparks (GPs), Natura 2000 sites, national parks (NPs), regional natural parks (RNPs), and Ramsar sites were selected because sufficient data (Table 2). From the remaining protected areas, two variables have been built (Table 1). The first, presence in protected area (PAP) simply translates the presence of a plot in a protected area or not. The second variable (PAT) indicates the type of protected area a plot lies in. To create the variable PAT, each plot has been assigned to one category. PAT_{None} if the plot is not in a protected area, PAT_{APB}, if the plot is in an APB, PAT_{BR} if the plot is in a BR, PAT_{GP} if the plot within a GP, PAT_{N2000} if it is on a Natura 2000 site, PAT_{NP} if the plot lies in a NP, PAT_{RNP} if the plot is in an RNP, PAT_{RS} if it is on a Ramsar site, and PAT_{Mixte} if the plot lies within several protected area. PAT has been created to reduce the interference between protected areas during the ANOVA analysis.

Table 2. Type of protection and number of plots in each protected area. Modified from Muséum national d'Histoire naturelle [Ed] (2003-2021). Note that one plot can lie in several protected area types at the same time.

Type of protection	*Protected area*	*Number of plots*
Regulative protection	Biotope protection orders	30
	Geotope protection orders	0
	Natural habitat protection orders	0
	Biological reserves	3
	National game reserves	3
	National natural reserves	6
	Regional natural reserves	2
Property control	Sites established by the coastal protection agency	0
Contractual protection	Regional natural parks	840
	National parks[1]	73
International convention	Natural or mixed sites from the World Heritage List by UNESCO	0
	Biosphere reserves	40
	Geoparks	146
	Ramsar sites	44
	Natura 2000 sites[2]	460

[1]The core area of national parks fall into the regulative protection category.

[2]Natura 2000 is a project from the European Union, but France chose a contractual protection to manage the sites on its territory.

Statistical analysis

Prior to the statistical analysis done with R (R Core Team, 2020), H_{max}, C_{μ}, BA, and stability have been natural-log transformed to fit normality assumptions, and standardised. The correlation between the different variables have also been calculated. Because the variables are of different types, different correlation analyses have been used, depending on the pair of variables analysed. When two dichotomous variables were analysed, the phi correlation method was used (Boslaugh, 2012). If at least one variable of the pair had more than two categories, the Cramer's V coefficient was used to assess the correlation between these variables (Boslaugh, 2012). In the case of one continuous variable and one dichotomous variable, the point-biserial correlation coefficient (Boslaugh, 2012), and if the second variable had more than two categories, the eta-squared coefficient was used (Richardson, 2011). When the two variables were continuous, the Pearson's *r* correlation was used (Boslaugh, 2012). Because of high level of correlation with basal area, the vertical structure ($\eta^2 = .27$), H_{max} [$r(4155) = .92$, $p < .001$], and C_{μ} [$r(4155) = .816$, $p < .001$] were discarded from the analysis.

A first step of the statistical analysis was to evaluate the influence of protected area. One-way ANOVA was run with stability as dependent variable and the presence of plots in or outside protected area (PAP) as independent variable, following the with-versus-without comparison proposed by Blackman (2013). A second ANOVA analysis was done to test the effect of protected area types (PAT) on temporal stability. Last, to analyse the influence of different variables on stability, a linear regression was used as suggested by Blackman (2013). The independent variables used can be divided in three categories: stand characteristics, ecological characteristics, and variables related to protected areas. Stand characteristics variables include the soil cover (SC), land use (LU), management marks (MM), incident type (IT), plantation type (PT), and skidding distance (SD). Ecological characteristics are number of species per plot (SP_{Ric}) and the basal area (BA). Variables related to protected areas are the presence or absence in biotope protection orders, biosphere reserves, geoparks, Natura 2000 sites, national parks, regional natural parks, and Ramsar sites. The presence or absence of plot within a protected areas has been incorporated in the linear model following the method of Salanié and Coisnon (2016).

Results

The one-way ANOVA analysis shows a significant difference of temporal stability between plots within a protected area or outside a protected area [$F(1, 4155) = 61.3$, $p < .001$)] (Figure 6). Furthermore, the type of protected area have a significant effect on temporal stability [$F(8, 4148) = 10.92$, $p < .001$] (Figure 7).

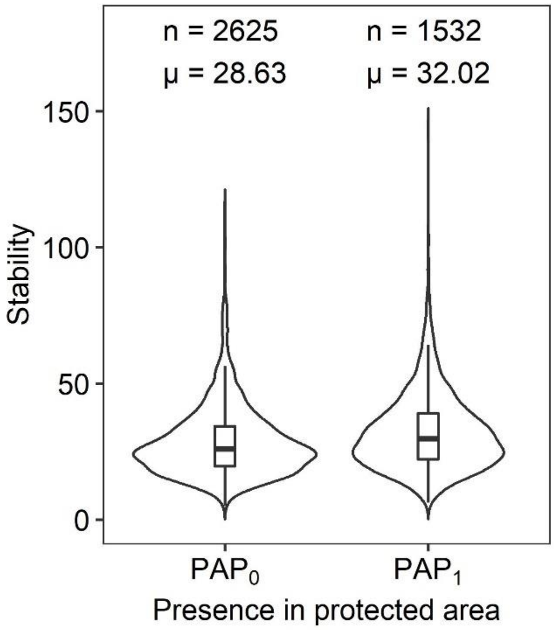

Figure 6. Boxplots representing the distribution of stability for plots outside protected areas (PAP_0) and inside protected areas (PAP_1). *n* represents the number of observations, and μ represents the mean stability for each parameter. The violin plot outlines represent the kernel probability density, i.e., the density of data located at each unit of stability.

The results of the linear regression (Table 3) shows that open woodland (SC_3) has a strong significant negative effect ($p < .001$) on temporal stability. In addition, the use of plots for hunt (LU_G) has also a significant negative effect on temporal stability ($p = .013$) compared to no use. Significant management marks (MM_2) show to have a significant positive impact on forest stability ($p = .003$). Tree mortality (IT_2) has also a significant positive impact on temporal stability ($p = .004$). Regular plantations with visible mesh (PT_P) and other plantation types (PT_X) have a significant negative impact on forest stability ($p < .001$ for both variables). A skidding distance between 200 m and 2 000 m (SD_1, SD_2, and SD_3) have a positive effect on temporal stability compared to a shorter skidding distance ($p < .001$ for all variables). Temporal stability is positively influenced by species richness (SP_{Ric}) and the total basal area (BA) of plots ($p = .030$ and $p < .001$, respectively). The presence of a plot in a biosphere reserve (BR), Natura 2000 site, or a regional natural park (RNP) has a significant positive impact on forest temporal stability ($p < .001$, $p < .001$, and $p = .005$, respectively).

Discussion

Stand and ecological characteristics

As expected, BA and SP_{Ric} have a positive influence of temporal stability. The effects of SP_{Ric} on stability are well documented. Species richness can increase stability through different processes such as species asynchrony, the portfolio effect, or overyielding. Tilman, Reich, and Knops (2006) and Polley, Isbell, and Wilsey (2013) reported an increase of stability with an increase of species richness, and Jucker et al. (2014) reported a decrease of aboveground wood production variability with the increase of species richness in central Europe. The species asynchrony and overyielding has been highlighted by Isbell et al. (2009) in grassland communities.

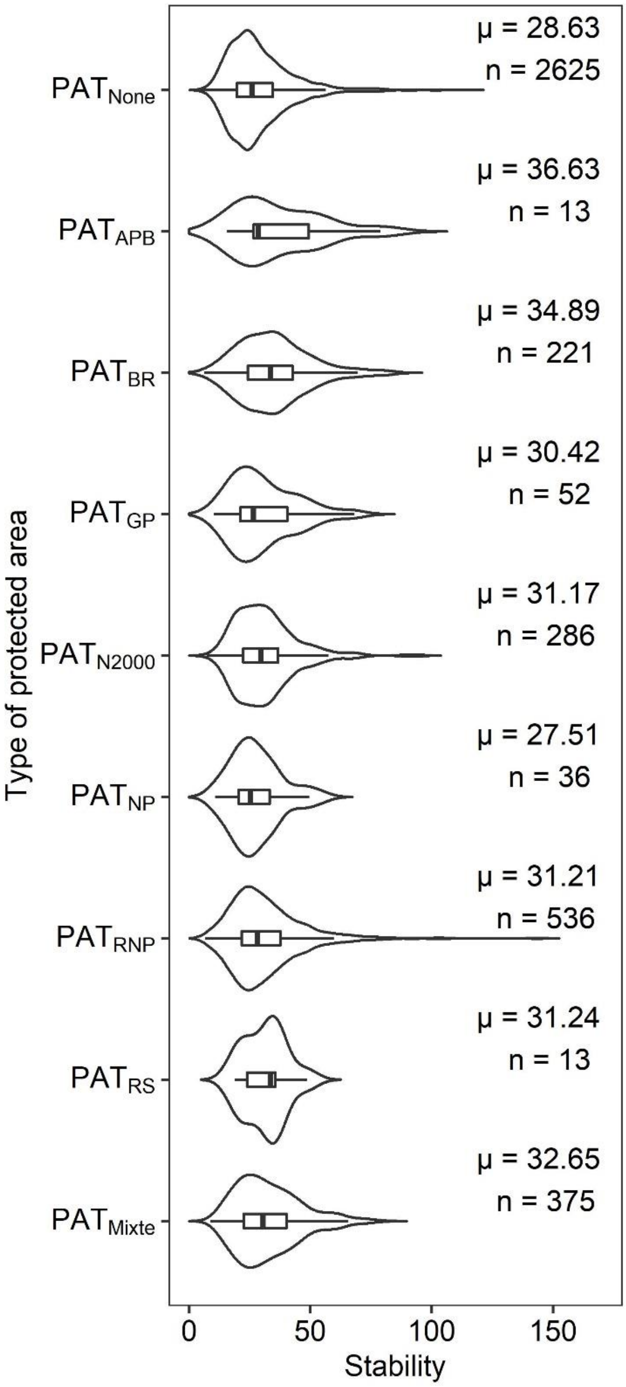

Figure 7. Boxplots representing the distribution of stability for plots within no protected area (PAT_{None}), exclusively within one type of protected area (PAT_{APB}, PAT_{BR}, PAT_{GP}, PAT_{N2000}, PAT_{NP}, PAT_{RNP}, PAT_{RS}), or within several type of protected area (PAT_{Mixte}). *n* represents the number of observations, and μ represents the mean stability for each parameter. The violin plot outlines represent the kernel probability density, i.e., the density of data located at each unit of stability.

BA can have a positive influence on temporal stability through the species asynchrony effect, as proposed by Dolezal et al. (2020). This positive effect can be supported by the negative influence of open woodland on stability. Indeed, open woodland are related to a lower species competition for light (Muscolo, Bagnato, Sidari, & Mercurio, 2014). Lower competition intensity for light within a community implies that species will be productive at similar moments, increasing the variability of productivity over time, and reducing the species asynchrony effect (Isbell et al., 2009; Meilhac, Deschamps, Maire, Flajoulot, & Litrico, 2020). BA has also a positive effect on tree mortality (Bradford & Bell, 2017; Prior, Murphy, & Russell-Smith, 2009). In addition to the link between demography and BA, there is positive effect of mortality found in the present study. Stephenson and van Mantgem (2005) and Stephenson et al. (2011) showed that mortality was positively correlated with forest productivity. This positive correlation can explain the positive relation between the observation of mortality and BA on stability.

The negative impact of hunting activities could indirectly show the impact of game specie on forest stability. Game species can have a negative impact on diversity and abundance of tree species (Reimoser & Gossow, 1996), and recruitment of new tree in the community (Vacek et al., 2019). Therefore, the presence of game could negatively influence stability by reducing its

Table 3. Predicted effect of independent variables on temporal stability (N = 4157). The predicted effects are shown with their associated estimate (B), standard-error (SE), and p-value (p). The parameter level SC_2 is not displayed as no plot of the analysis fell in this category. Note that one plot can lie in several protected area types at the same time. See table 1 for abbreviation meaning.

Predictors		*B*	*SE*	*p*
Intercept		-0.29	0.05	<.001
Soil cover (SC):	SC_3	-0.47	0.12	<.001
[Ref. cat: SC_1]				
Land use (LU):	LU_A	-0.08	0.08	.365
[Ref. cat: LU_0]	LU_F	0.06	0.96	.948
	LU_G	-0.35	0.14	.013
	LU_L	-0.13	0.16	.400
	LU_M	-0.30	0.23	.191
	LU_R	0.16	0.29	.587
	LU_T	-0.24	0.34	.483
Management mark (MM):	MM_1	0.00	0.04	.997
[Ref. cat: MM_0]	MM_2	0.12	0.04	.003
Incident type (IT):	IT_1	0.71	0.43	.103
[Ref. cat: IT_0]	IT_2	0.24	0.08	.004
	IT_3	0.31	0.56	.573
	IT_4	-0.02	0.09	.790
	IT_5	0.09	0.15	.542
Plantation type (PT):	PT_P	-0.33	0.07	<.001
[Ref. cat: PT_0]	PT_Q	-0.07	0.07	.309
	PT_X	-0.35	0.09	<.001
Skidding distance (SD):	SD_1	0.15	0.03	<.001
[Ref. cat: SD_0]	SD_2	0.31	0.05	<.001
	SD_3	0.38	0.07	<.001
	SD_4	0.18	0.13	.172
SP_{Ric}		0.02	0.01	.030
BA		0.15	0.02	<.001
Presence in APB		0.14	0.18	.445
Presence in BR		0.40	0.05	<.001
Presence in GP		0.01	0.08	.896
Presence on N2000 site		0.21	0.05	<.001
Presence in NP		0.12	0.12	.296
Presence in RNP		0.11	0.04	.005
Presence on Ramsar site		-0.12	0.15	.434
R^2				0.087
R^2_{adj}				0.081

components, mean productivity and its variation. However, Reimoser and Gossow (1996) reported that negative impact of game is dependent of the type of forest management. The positive influence of the presence of management marks is surprising as plantation type has a negative influence on stability in the results. Forest plantations can negatively influence stability by decreasing species richness and the overyielding effect (Chaudhary, Burivalova, Koh, & Hellweg, 2016; Jonsson et al., 2019; Jucker et al., 2014). Moreover, the type of management such as clear-cutting can have a negative impact on species richness (Chaudhary et al., 2016), leading to a decrease of stability. The positive effect of increased skidding distance on stability can be due to the decrease of economic benefits of exploiting remote forest patched. Indeed Deininger and Minten (2002) and Cropper, Puri, and Griffiths (2001) highlighted that closer is a forest to the road, higher is its probability to be deforested.

Protected areas

The effect of protected areas on forest ecosystems is well documented (Bruner, Gullison, Rice, & da Fonseca, 2001; Deininger & Minten, 2002; Joppa & Pfaff, 2011). Some results could appear surprising such as the absence of significant effect of NPs on forest stability. However, such results should be interpreted in the light of France’s management of its protected area. The absence of effect from APBs could be due to their small size, as 75% of APBs are less than 1 km^2 (Léonard et al., 2018), but mostly likely because they may not efficiently protect forests, as most of them are considered as outdated and should be reviewed (Léonard et al., 2018). Moreover, the absence of conservation or restoration measures implemented on APB sites (Léonard et al., 2018) may not contribute to enhance stability of plots. Stability is not influenced by GPs. This result is not surprising as the aim of geoparks is to protect geological heritage (Mc Keever & Zouros, 2005), and five of them were created after 2012, relatively late in the temporal scope of this study (Muséum national d'Histoire naturelle [Ed], 2003-2021). The non-significant effect could also show that even if GPs aim to enhance local economy via tourism (Farsani et al., 2011), the absence of direct measures to protect biodiversity cannot significantly enhance forest stability. In the same line, the absence of significant effect of Ramsar sites could have the same explanation. Indeed, Ramsar sites emerged from an international convention initially aiming for the protected of water birds and their habitats, wetlands (Ministère de la Transition écologique, 2021b).

The absence of significant effect of NPs could be explained by several reasons. First, the data do not distinguish between core area and area of partnership in the analysis. This lack of distinction between the two areas might be a reason for the non-significant effect of NP on stability. Indeed, core area and area of partnership, although linked by ecological solidarity (Amara, 2008), do not have the same type of activities occurring within their space. The core area is oriented toward biodiversity conservation, with stricter rules than the area of partnership, oriented toward sustainable development (Lefebvre & Moncorps, 2010). Second, NPs are under the control of the central State, and the creation of national parks often led to conflict because of a lack of consultation with local population on the delimitation, objectives and regulations of NPs (Cadoret, 2017; Clarimont, 2013). These conflicts and the mediation ensued from them might lead to insufficient conservation action to enhance forest temporal stability.

The positive influence of BRs, RNPs, and Natura 2000 sites could be attributed to their local management. Indeed, BRs are often geographically superposed to RNPs and managed by their mixed unions (Lefebvre & Moncorps, 2010; Muséum national d'Histoire naturelle [Ed], 2003-2021). In addition, RNPs emerged from a local will to protected natural heritage, leading to the establishment of a local level of governance and high level of participation from stakeholders (Parra, 2010). For instance, this involvement allowed to introduce a sustainable forest management in the RNP *des Vosges du nord* (Genot, 2006). The positive impact of Natura 2000 sites could also be imputed to their local management. Even if Natura 2000 sites originated from a European policy, the conflicts that occurred during their implementation resulted in a strong local management with an important involvement of local stakeholders through the use of Natura 2000 contracts and charters (Alphandery & Fortier, 2001). The use of contracts and charters can create a greater involvement in conservation measures by local stakeholder and a more specific management of each sites (Allag Dhuisme et al., 2015) leading to a greater forest stability. However, Anthon, Garcia, and Stenger (2010) also showed that the use of economic incentives to promote conservation measures could have limitations. From the different responses of stability to protected area types, it is possible to suppose that protected areas with a local governance and specific actions toward forest conservation can have significantly influence the stability of forest.

Limits of stability

Even though there is a sensibility of forest temporal stability to the type of protected area a forest lies in, the present results need to be interpreted with caution. The superposition of the different protected areas, physically and legislatively, can possibly create interferences in the results. Indeed, 375 plots are lying within at least two protected areas (Figure 7), and many protected areas are often created on top of each other for diverse reasons (Figures 1, 2 & 5). This administrative *millefeuille* of protected areas can lead a complex legislative framework that creates difficulties to implement any conservation action and to assess their causality on stability (Allag Dhuisme et al., 2015; Mathevet et al., 2020). In addition, there is no consensus on measuring the success of protected areas. For instance, the Natura 2000 network possesses its own framework, created by the European Union, to assess the state of a site, but it has been qualified as complicated to understand, and therefore it is little used (Allag Dhuisme et al., 2015). Concerning French protected areas, there is no official systematic review system for APBs, RNPs, or NPs, and their state is often assessed on a case-by-case basis (Allag Dhuisme et al., 2015; Genot, 2006; Lajarge, 1997). This absence of possible comparison affects negatively the validity of stability as a tool to measure the state of forest ecosystem in protected areas (Bryman, 2016).

Temporal stability also needs to be used with caution. Firstly, it is an indicator related to the productivity of vegetation. Even if temporal stability can be measured for virtually all vegetation, it is limited to this type of ecosystem. Moreover, stability assesses only the state of the forested part of a protected area in the study. Therefore, the state of other ecosystems such as grassland or lake potentially present in the protected area is unknown, leading to the impossibility to conclude on the general ecological state of the protected area. Secondly, the spatial mismatch between MODIS pictures and plot size can lead to the incorporation of other ecosystems in the analysis and influence negatively the validity of stability (Bryman, 2016). However, this problem should be avoided by selecting the valid range of NDVI value provided by MODIS and focusing the NDVI collection on the forested plots provided by the national forest inventory. Nonetheless, the use of forest inventory data to measure stability implies that a complete inventory of the country's forests should be done regularly. The inventory also bonds the study to plots chosen by the institution leading the inventory, and any change in plot location decided by this institution will alter the reliability of the study (Bryman, 2016). Nonetheless, temporal stability responds well to the type of protected areas and could be used to create a tool such as an index indicating the good or bad state of a forest.

Conclusion

Forest temporal stability, in addition to be sensitive to ecological variables, is also responding to the management and the protected status of the forest. Thanks to these characteristics, stability could be a suitable tool to measure the long-term effectiveness of protected areas. However, temporal stability focuses mainly on vegetation, and in this case forest. Therefore, it needs to be integrated in a broader framework to be used as a tool to assess the ecological state of a protected area. For further investigation, this tool could be used to create a stability index, that could assess the state of a forest and give an easy-to-interpret tool for policy makers in order to establish necessary actions for forest conservation.

References

Adams, W. M. (2019). Geographies of conservation III: Nature's spaces. *Progress in Human Geography, 44*(4), 789-801. doi:10.1177/0309132519837779

Adams, W. M., & Hutton, J. (2007). People, Parks and Poverty: Political Ecology and Biodiversity Conservation. *Conservation & Society, 5*(2), 147-183. Retrieved from https://www.jstor.org/stable/26392879

Alcoulombre, E. (2016). *Les sites Ramsar français : état des lieux d'un réseau français d'importance internationale*. Retrieved from https://www.ecologie.gouv.fr/protection-des-milieux-humides

Allag Dhuisme, F., Barthod, C., Domallain, D., Jourdier, G., Reichert, P., & Velluet, R. (2015). *Analyse du dispositif Natura 2000 en France*. Retrieved from

Alphandery, P., & Fortier, A. (2001). Can a Territorial Policy be Based on Science Alone? The System for Creating the Natura 2000 Network in France. *Sociologia Ruralis, 41*(3), 311-328. doi:10.1111/1467-9523.00185

Amara, H. (2008). *Les parcs nationaux de France, territoires de références*(Parcs Nationaux de France ed., pp. 28). Retrieved from http://www.parcsnationaux.fr/fr/des-decouvertes/les-parcs-nationaux-de-france/lorganisation-du-territoire-dun-parc-national-francais

Anthon, S., Garcia, S., & Stenger, A. (2010). Incentive Contracts for Natura 2000 Implementation in Forest Areas. *Environmental and Resource Economics, 46*(3), 281-302. doi:10.1007/s10640-009-9341-1

Barbero, M., Bonin, G., Loisel, R., & Quézel, P. (1990). Changes and disturbances of forest ecosystems caused by human activities in the western part of the mediterranean basin. *Vegetatio, 87*(2), 151-173. doi:10.1007/BF00042952

BDRH conseils, Parc nationaux de France, & L'atelier technique des espaces naturels. (2011). *Référentiel des métiers - Parcs nationaux de France*(pp. 161). Retrieved from http://www.parcsnationaux.fr/fr/des-decouvertes/les-parcs-nationaux-de-france/lorganisation-administrative-dun-parc-national

Blackman, A. (2013). Evaluating forest conservation policies in developing countries using remote sensing data: An introduction and practical guide. *Forest Policy and Economics, 34*, 1-16. doi:10.1016/j.forpol.2013.04.006

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science, 320*(5882), 1444-1449. doi:10.1126/science.1155121

Boslaugh, S. (2012). *Statistics in a Nutshell* (M. Treseler Ed. 2nd Edition ed.). USA: O'Reiley Media.

Bouamrane, M., Spierenburg, M., Agrawal, A., Boureima, A., Cormier-Salem, M.-C., Etienne, M., . . . Mathevet, R. (2016). Stakeholder engagement and biodiversity conservation challenges in social-ecological systems: some insights from biosphere reserves in western Africa and France. *Ecology and Society, 21*(4). doi:10.5751/es-08812-210425

Bradford, J. B., & Bell, D. M. (2017). A window of opportunity for climate-change adaptation: easing tree mortality by reducing forest basal area. *Frontiers in Ecology and the Environment, 15*(1), 11-17. doi:10.1002/fee.1445

Brekke, C., & Solberg, A. H. S. (2005). Oil spill detection by satellite remote sensing. *Remote Sensing of Environment, 95*(1), 1-13. doi:10.1016/j.rse.2004.11.015

Brooks, T. M., Wright, S. J., & Sheil, D. (2009). Evaluating the Success of Conservation Actions in Safeguarding Tropical Forest Biodiversity. *Conservation Biology, 23*(6), 1448-1457. doi:10.1111/j.1523-1739.2009.01334.x

Bruner, A. G., Gullison, R. E., Rice, R. E., & da Fonseca, G. A. (2001). Effectiveness of parks in protecting tropical biodiversity. *Science, 291*(5501), 125-128. doi:10.1126/science.291.5501.125

Bryman, A. (2016). *Social Research Methods* (5th ed.). New York: Oxford University Press.

Burtenshaw, J. C., Oleson, E. M., Hildebrand, J. A., McDonald, M. A., Andrew, R. K., Howe, B. M., & Mercer, J. A. (2004). Acoustic and satellite remote sensing of blue whale seasonality and habitat in the Northeast Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography, 51*(10-11), 967-986. doi:10.1016/s0967-0645(04)00095-5

Cadoret, A. (2017). Des conflits territoriaux révélateurs d'efforts différenciés de protection de l'environnement : le cas du Parc National des Ca-lanques (France). *Canadian Journal of Regional Science / Revue canadienne des sciences régionales, 40*(2), 185-194. Retrieved from https://idjs.ca/wp-content/uploads/V40N2-CADORET.pdf
Chaudhary, A., Burivalova, Z., Koh, L. P., & Hellweg, S. (2016). Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Scientific Reports, 6*(1), 23954. doi:10.1038/srep23954
Clarimont, S. (2013). La patrimonialisation des espaces naturels en débat : la réforme du Parc national des Pyrénées (France). *VertigO*(Hors-série 16). doi:10.4000/vertigo.13549
Code de l'environnement. (2021). Retrieved from https://www.legifrance.gouv.fr/codes/texte_lc/LEGITEXT000006074220/2021-05-02/
Comba, D. (2011). Le régime légal des réserves MAB en France. *Revue juridique de l'environnement, 36*(3), 297-304. Retrieved from https://www.cairn.info/revue-revue-juridique-de-l-environnement-2011-3-page-297.htm
Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., . . . Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change, 26*, 152-158. doi:10.1016/j.gloenvcha.2014.04.002
Cropper, M., Puri, J., & Griffiths, C. (2001). Predicting the Location of Deforestation: The Role of Roads and Protected Areas in North Thailand. *Land Economics, 77*(2), 172-186. doi:10.2307/3147088
Curt, T., Fréjaville, T., & Lahaye, S. (2016). Modelling the spatial patterns of ignition causes and fire regime features in southern France: implications for fire prevention policy. *International Journal of Wildland Fire, 25*(7). doi:10.1071/wf15205
De Heer, M., Kapos, V., Miles, L., & Ten Brink, B. (2004). Biodiversity Trends and Threats in Europe – Can We Apply a Generic Biodiversity Indicator to Forests? In M. Marchetti (Ed.), *Monitoring and indicators of Forest Biodiversity in Europe - From Ideas to Operationality* (Vol. EFI Proceedings No. 51, pp. 15-26). Finland: European Forest Institute.
Deininger, K., & Minten, B. (2002). Determinants of Deforestation and the Economics of Protection: An Application to Mexico. *American Journal of Agricultural Economics, 84*(4), 943-960. doi:10.1111/1467-8276.00359
Didan, K. (2015). *MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006*.
Didan, K., Barreto Munoz, A., Solano, R., & Huete, A. (2015). MODIS Vegetation Index User's Guide. In (pp. 35).
Direction de l'eau et de la biodiversité. (2010). *Circulaire DGALN DEB/SDEN/BMA-DGOM du 24 décembre 2009 relative à la mise en œuvre de laconvention internationale de Ramsar sur les zones humides et notamment processus d'inscription de zones humides au titre de cette convention*. Retrieved from https://www.bulletin-officiel.developpement-durable.gouv.fr/notice?id=Bulletinofficiel-0024019&reqId=6bc2fef5-dbb1-4d51-83de-fb40f9735e70&pos=4
Dolezal, J., Fibich, P., Altman, J., Leps, J., Uemura, S., Takahashi, K., & Hara, T. (2020). Determinants of ecosystem stability in a diverse temperate forest. *Oikos, 129*(11), 1692-1703. doi:10.1111/oik.07379
Dudley, N., Shadie, P., & Stolton, S. (2013). *Guidelines for applying protected area management categories including IUCN WCPA best practice guidance on recognising protected areas and assigning management categories and governance types* (N. Dudley Ed. Vol. 21). Switzerland: IUCN.
Farsani, N. T., Coelho, C., & Costa, C. (2011). Geotourism and geoparks as novel strategies for socio-economic development in rural areas. *International Journal of Tourism Research, 13*(1), 68-81. doi:10.1002/jtr.800
Fédération des Parcs Naturels Régionaux de France. (2021). Parcs naturels régionaux de France. Retrieved from https://www.parcs-naturels-regionaux.fr/
Ford, C. (2004). Nature, Culture and Conservation in France and Her Colonies 1840-1940. *Past & Present*(183), 173-198. Retrieved from https://www.jstor.org/stable/3600863

Garcia-Palacios, P., Gross, N., Gaitan, J., & Maestre, F. T. (2018). Climate mediates the biodiversity-ecosystem stability relationship globally. *Proceedings of the National Academy of Sciences, 115*(33), 8400-8405. doi:10.1073/pnas.1800425115

Genot, B. (2006). Gestion forestière dans le parc naturel régional des Vosges du Nord, réserve de biosphère. *Revue Forestière Française*(Spécial - Gestion de la biodiversité), 235-244. doi:10.4267/2042/5302

Guide relatif à la gestion des sites Natura 2000 majoritairement terrestres. (2019). Retrieved from https://www.ecologie.gouv.fr/reseau-europeen-natura-2000-1

IGN. (2005). Inventaire forestier national français, Données brutes, Campagnes annuelles 2005 et suivantes. Retrieved from https://inventaire-forestier.ign.fr/spip.php?rubrique159

IGN. (2020). Le mémento, inventaire forestier - Edition 2020. In (pp. 36). Paris.

Isbell, F. I., Polley, H. W., & Wilsey, B. J. (2009). Biodiversity, productivity and the temporal stability of productivity: patterns and processes. *Ecology Letters, 12*(5), 443-451. doi:10.1111/j.1461-0248.2009.01299.x

Jamet, S. (2007). *Faire face aux défis de la décentralisation en France* (571). Retrieved from https://www.oecd-ilibrary.org/economics/faire-face-aux-defis-de-la-decentralisation-en-france_125763645442

Jonsson, M., Bengtsson, J., Gamfeldt, L., Moen, J., & Snall, T. (2019). Levels of forest ecosystem services depend on specific mixtures of commercial tree species. *Nat Plants, 5*(2), 141-147. doi:10.1038/s41477-018-0346-z

Joppa, L. N., & Pfaff, A. (2011). Global protected area impacts. *Proceedings of the Royal Society B, 278*(1712), 1633-1638. doi:10.1098/rspb.2010.1713

Jucker, T., Bouriaud, O., Avacaritei, D., & Coomes, D. A. (2014). Stabilizing effects of diversity on aboveground wood production in forest ecosystems: linking patterns and processes. *Ecology Letters, 17*(12), 1560-1569. doi:10.1111/ele.12382

Lajarge, R. (1997). Environnement et processus de territorialisation : le cas du Parc naturel régional de la Chartreuse (France)/ The environment and the process of territorialisation : the case of the Chartreuse regional natural park (France). *Revue de géographie alpine, 85*(2), 131-144. doi:10.3406/rga.1997.3916

Larsen, J. B. (1995). Ecological stability of forests and sustainable silviculture. *Forest Ecology and Management, 73*(1-3), 85-96. doi:10.1016/0378-1127(94)03501-m

Lefebvre, T., & Moncorps, S. (2010). *Les espaces protégés français : une pluralité d'outils au service de la conservation de la biodiversité*. Paris, France: Comité français de l'UICN.

Lehman, C. L., & Tilman, D. (2000). Biodiversity, Stability, and Productivity in Competitive Communities. *The American Naturalist, 156*(5), 534-552. doi:10.1086/303402

Léonard, L., Rouveyrol, P., Grech, G., Chanet, C., & Hérard, K. (2018). *Les Arrêtés Préfectoraux de Protection de Biotope (APPB): état des lieux du réseau national et de la mise en œuvre de l'outil*. Retrieved from Paris:

Léonard, L., Witté, I., Rouveyrol, P., & Hérard, K. (2020). *Représentativité et lacunes du réseau d'aires protégées métropolitain terrestre au regard des enjeux de biodiversité*. Retrieved from Paris:

Lepš, J., de Bello, F., Šmilauer, P., & Doležal, J. (2011). Community trait response to environment: disentangling species turnover vs intraspecific trait variability effects. *Ecography, 34*(5), 856-863. doi:10.1111/j.1600-0587.2010.06904.x

Lindenmayer, D. B., Margules, C. R., & Botkin, D. B. (2000). Indicators of Biodiversity for Ecologically Sustainable Forest Management. *Conservation Biology, 14*(4), 941-950. doi:10.1046/j.1523-1739.2000.98533.x

Loi du 21 avril 1906 organisant la protection des sites et monuments naturels de caractère artistique

Loi n°60-708 du 22 juillet 1960 relative à la création de parcs nationaux (J.O. du 23 juillet 1960)

Loi n°76-629 du 10 juillet 1976 relative à la protection de la nature (J.O. 13 juillet 1976)

Loi n°93-24 du 8 janvier 1993 sur la protection et la mise en valeur des paysages et modifiant certaines dispositions législatives en matière d'enquêtes publiques (J.O. 9 janvier 1993)

Loi n°2016-1087 du 8 août 2016 pour la reconquête de la biodiversité, de la nature et des paysages (J.O. 9 août 2016)

Madrigal-González, J., Herrero, A., Ruiz-Benito, P., & Zavala, M. A. (2017). Resilience to drought in a dry forest: Insights from demographic rates. *Forest Ecology and Management, 389*, 167-175. doi:10.1016/j.foreco.2016.12.012

Mathevet, R., Cibien, C., & Atramentowicz, M. (2020). Les réserves de bioshpère françaises. Vers une écologie solidaire et une gestion responsable. In (pp. 10). Paris: MAB France.

Mc Keever, P. J., & Zouros, N. (2005). Geoparks: Celebrating Earth heritage, sustaining local communities. *Episodes, 28*(4), 274-278. doi:10.18814/epiiugs/2005/v28i4/006

McCauley, D. (2008). Sustainable development and the 'governance challenge': the French experience with Natura 2000. *European Environment, 18*(3), 152-167. doi:10.1002/eet.478

Meilhac, J., Deschamps, L., Maire, V., Flajoulot, S., & Litrico, I. (2020). Both selection and plasticity drive niche differentiation in experimental grasslands. *Nature Plants, 6*(1), 28-33. doi:10.1038/s41477-019-0569-7

Ministère de la Transition écologique. (2017, 28/08/17). Loi pour la reconquête de la biodiversité, de la nature et des paysages. Retrieved from https://www.ecologie.gouv.fr/loi-reconquete-biodiversite-nature-et-des-paysages

Ministère de la Transition écologique. (2019, 09/08/19). Réseau européen Natura 2000. Retrieved from https://www.ecologie.gouv.fr/reseau-europeen-natura-2000-1

Ministère de la Transition écologique. (2020). *Note technique du 08 Janvier 2020 relative aux arrêtés préfectoraux de protection des biotopes et des habitats naturels*. Retrieved from https://www.ecologie.gouv.fr/sites/default/files/Note_technique_arretes_prefectoraux_protection_biotopes_et_habitats_naturels_8_janvier_2020.pdf

Ministère de la Transition écologique. (2021a, 15/03/21). Plan biodiversité. Retrieved from https://www.ecologie.gouv.fr/plan-biodiversite

Ministère de la Transition écologique. (2021b, 03/02/21). Protection des milieux humides. Retrieved from https://www.ecologie.gouv.fr/protection-des-milieux-humides

Ministère de la Transition écologique, Ministère de la mer, & biodiversité, O. f. d. l. (2021). *Stratégie nationale pour les aires protégées 2030*. Retrieved from https://ofb.gouv.fr/la-strategie-nationale-pour-les-aires-protegees

Moral, V., Clap, F., Ritossa, S., & Moncorps, S. (2016). *Decentralised cooperation and biodiversity, scaling up French local government action abroad for biodiversity conservaiton*. Retrieved from https://www.diplomatie.gouv.fr/en/french-foreign-policy/climate-and-environment/sustainable-development-environment/french-policy-on-biodiversity/decentralised-cooperation-and-biodiversity/

Muscolo, A., Bagnato, S., Sidari, M., & Mercurio, R. (2014). A review of the roles of forest canopy gaps. *Journal of Forestry Research, 25*(4), 725-736. doi:10.1007/s11676-014-0521-7

Muséum national d'Histoire naturelle [Ed]. (2003-2021). Inventaire National du Patrimoine Naturel. Retrieved from https://inpn.mnhn.fr

Noss, R. F. (1990). Indicators for Monitoring Biodiversity: A Hierarchical Approach. *Conservation Biology, 4*(4), 355-364. Retrieved from http://www.jstor.org/stable/2385928

OCDE. (2016). *Examens environnementaux de l'OCDE : France 2016* (OCDE Ed.). Paris: OCDE.

Office français de la biodiversité. (2021a, 11/02/2021). La stratégie nationale pour les aires protégées. Retrieved from https://ofb.gouv.fr/la-strategie-nationale-pour-les-aires-protegees

Office français de la biodiversité. (2021b). Portail des parcs nationaux de France. Retrieved from http://www.parcsnationaux.fr/fr

Office national des forêts. (2015). Le déficit foliaire : un outil pour caractériser la vitalité des arbres. Retrieved from http://www1.onf.fr/renecofor/sommaire/resultats/climat/letat-du-feuillage/20151015-093738-857966/@@index.html

Parra, C. (2010). Sustainability and multi-level governance of territories classified as protected areas in France: the Morvan regional park case. *Journal of Environmental Planning and Management, 53*(4), 491-509. doi:10.1080/09640561003737341

Pernet, A. (2019). Retracer une démarche de médiation paysagère pour mieux l'évaluer : expérimentation dans un secteur à controverses environnementales. Les Ateliers Grand site Marais mouillé poitevin. *Développement durable et territoires, 10*(2). doi:10.4000/developpementdurable.14309

Polley, H. W., Isbell, F. I., & Wilsey, B. J. (2013). Plant functional traits improve diversity-based predictions of temporal stability of grassland productivity. *Oikos, 122*(9), 1275-1282. doi:10.1111/j.1600-0706.2013.00338.x
Polovina, J. J., Howell, E., Kobayashi, D. R., & Seki, M. P. (2001). The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography, 49*(1-4), 469-483. doi:10.1016/s0079-6611(01)00036-2
Prior, L. D., Murphy, B. P., & Russell-Smith, J. (2009). Environmental and demographic correlates of tree recruitment and mortality in north Australian savannas. *Forest Ecology and Management, 257*(1), 66-74. doi:10.1016/j.foreco.2008.08.015
QGIS.org. (2021). QGIS Geographic Information System: QGIS Association. Retrieved from http://www.qgis.org
R Core Team. (2020). R: A Language and Environment for Statistical Computing: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/
Reimoser, F., & Gossow, H. (1996). Impact of ungulates on forest vegetation and its dependence on the silvicultural system. *Forest Ecology and Management, 88*(1), 107-119. doi:10.1016/S0378-1127(96)03816-9
Richardson, J. T. E. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review, 6*(2), 135-147. doi:10.1016/j.edurev.2010.12.001
Salanié, J., & Coisnon, T. (2016). *Environmental Zoning and Urban Development: Natural Regional Parks in France* (110). Retrieved from
Shvidenko, A., Barber, C. V., Persson, R., Gonzalez, P., Hassan, R., Lakyda, P., . . . Scholes, B. (2005). Forest and Woodland Systems. In R. Hassan, R. Scholes, & N. Ash (Eds.), *Ecosystems and Human Well-being: Current State and Trends* (Vol. 1, pp. 37): Island Press.
Simberloff, D. (1998). Flagships, umbrellas, and keystones: Is single-species management passé in the landscape era? *Biological Conservation, 83*(3), 247-257. doi:10.1016/s0006-3207(97)00081-5
Stephenson, N. L., & van Mantgem, P. J. (2005). Forest turnover rates follow global and regional patterns of productivity. *Ecology Letters, 8*(5), 524-531. doi:10.1111/j.1461-0248.2005.00746.x
Stephenson, N. L., van Mantgem, P. J., Bunn, A. G., Bruner, H., Harmon, M. E., O'Connell, K. B., . . . Franklin, J. F. (2011). Causes and implications of the correlation between forest productivity and tree mortality rates. *Ecological Monographs, 81*(4), 527-555. doi:https://doi.org/10.1890/10-1077.1
Stratégie nationale pour la biodiversité 2011-2020. (2012). Citizen Press Retrieved from https://www.ecologie.gouv.fr/strategie-nationale-biodiversite
Streib, N. (2019). *Les Parcs naturels régionaux de France - Présentation*(pp. 62). Retrieved from https://www.parcs-naturels-regionaux.fr/sites/federationpnr/files/document/centre_de_ressources/PNR_plaq_pr%C3%A9s_2021_web.pdf
Tilman, D. (1999). The ecological consequences of changes in biodiversity: a search for general principles. *Ecology, 80*(5), 1455-1474. doi:10.1890/0012-9658(1999)080
Tilman, D., Reich, P. B., & Knops, J. M. (2006). Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature, 441*(7093), 629-632. doi:10.1038/nature04742
Trumbore, S., Brando, P., & Hartmann, H. (2015). Forest health and global change. *Science, 349*(6250), 814-818. doi:10.1126/science.aac6759
UNESCO. (2017). UNESCO Global Geoparks. Retrieved from http://www.unesco.org/new/en/natural-sciences/environment/earth-sciences/unesco-global-geoparks/
UNESCO. (2019). Biosphere Reserves. Retrieved from https://en.unesco.org/biosphere
Vacek, S., Prokůpková, A., Vacek, Z., Bulušek, D., Šimůnek, V., Králíček, I., . . . Hájek, V. (2019). Growth response of mixed beech forests to climate change, various management and game pressure in Central Europe. *Journal of Forest Science, 65*(No. 9), 331-345. doi:10.17221/82/2019-jfs
Wales, S. B., Kreider, M. R., Atkins, J., Hulshof, C. M., Fahey, R. T., Nave, L. E., . . . Gough, C. M. (2020). Stand age, disturbance history and the temporal stability of forest production. *Forest Ecology and Management, 460*. doi:10.1016/j.foreco.2020.117865

Wang, J., Rich, P. M., Price, K. P., & Kettle, W. D. (2004). Relations between NDVI and tree productivity in the central Great Plains. *International Journal of Remote Sensing, 25*(16), 3127-3138. doi:10.1080/0143116032000160499

Wheater, C. P., Beel, J. R., & Cook, P. A. (2011). Sampling Static Organisms. In C. P. Wheater, J. R. Beel, & P. A. Cook (Eds.), *Practical Field Ecology: A Project Guide* (pp. 67-94). UK: Wiley-Blackwell.

Zarnoch, S. J., Bechtold, W. A., & Stolte, K. W. (2004). Using crown condition variables as indicators of forest health. *Canadian Journal of Forest Research, 34*(5), 1057-1070. doi:10.1139/x03-277

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