CRREF Collective Expert Assessment: Clearcuts and Renewal of Forest Stands in the Context of Climate Change (*Coupes Rases et REnouvellement des peuplements Forestiers en contexte de changement climatique)*

Summary Report of Collective Assessment - June 2023

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This summary, together with the expert assessment report and the presentations from the feedback Seminar, are available on the GIP Ecofor website (http://www.gip-ecofor.org/).

To cite this document:
Landmann, G., Delay, M., Marquet, G. (Coord.), Bergès, L., Collet, C., Deuffic, P., Gosselin, M., Marage, D., Ogée, J., Ose, K., Perrier, C. (Leaders), Agro, C., Akroume, E ., Aubert, M., Augusto, L., Baubet, O., Becquey, J., Belouard, T., Boulanger, V., Bourdin, A., Boutte, B., Bouwen, K., Brault, S., Brunet, Y., Bureau, F., Castro, A., Chaumet, M., Conche, J., Darboux, F., Depeige, L., Desgroux, A., Dokhelar, T., Domec, J.-C., Dumas, Y., Duprez, M., Frappart, F., Garcia, S., Gardiner, B., Girard, S., Gosselin, F., Husson, C., Jacomet, E., Jactel, H., Joyeau, C., Lacombe, E., Laurent, L., Legout, A., Lelasseur, L., Lousteau, D., Meredieu, C., Moreews, L., Orazio, C., Peyron, J.-L., Pilard-Landeau, B., Pitaud, J., Planells, M., Plat, N., Ponette, Q., Pousse, N., Prévosto, B., Puiseux, J., Puyal, M., Ranger, J., Richou, E., Rigolot, E., Riou-Nivert, P., Saïd, S., Saintonge, F.-X., Serra Diaz, J.-M., Stemmelen, A., Toutchkov, M., van Halder, I., Vincenot, L., Wurpillot, S. (Experts). 2023 *Expertise collective CRREF "Coupes Rases et Renouvellement des peuplements Forestiers en contexte de changement climatique", Synthèse de l'expertise*, Paris: GIP ECOFOR, RMT AFORCE, 87 pages.
ISBN: 978-2-91-4770-19-4
Graphic design: Léa Chevrier.

[1] The affiliations of contributors to the Expert Assessment are detailed at the end of this report.

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General introduction

General background, Issues and Objectives

Over the past ten years or so, government administrations, forestry and wood industry players, and environmental NGOs have been heavily involved in strategic initiatives, from the National Forest and Wood Plan (2017) to the Forest and Wood Conference (2022). The current context is marked by a global environmental crisis, prompting the immediate implementation of an **ambitious policy of adaptation to climate change** while preserving forest biodiversity as part of sustainable, multifunctional forest management, which is the cornerstone of French forestry policy. There is both continuity with the objective that these partners had set 15 years ago in the context of the Grenelle Environment Forum (2007), i.e. "to produce more (wood) while better preserving biodiversity", and a disruptive change insofar as today's issues are more acute.

In parallel, there has been growing societal tension and unprecedented media coverage about elements regarded as signs of intensifying forest management and artificialisation of stands. These include among other **clearcutting, plantations in general and pure conifer plantations in particular, especially where they replace broadleaved stands**. The issue of clearcutting is now the subject of numerous and often heated debates, as well as dedicated political initiatives: the report from a parliamentary mission to the Prime Minister drafted by Anne-Laure Catellot (LRM) (2020), the Bill on the regulation of clearcutting by Mathilde Panot (LFI) and the Citizens' Convention (2020) all call for a sharp reduction in its use. These requests have so far gone unanswered.

While the issue of **forest renewal** was progressing steadily in the various strategic documents, it was not until the "*Assises de la Forêt et du Bois*" (2022) conference that the issue of clearcutting came to the fore, with some fifteen explicit references to clearcutting from environmental NGOs[2], Regions and the forestry & timber industry (Cattelot *et al.*, 2022). They address the need for a legitimate and credible forum for debates on various topics, including clearcutting, the need for mapping clearcuts, the conditionality of aid, and the supervision of clearcuts.

The need to launch a project on this issue was prompted by the fact that the subject is currently highly controversial, but **little documented scientifically** in the French context: at best, we can cite the summary by Barthod *et al.* (1999) in *Revue forestière française*, an analysis of the influence of forest clear-felling on biodiversity by Bergès published by Gosselin and Laroussinie (2004) on "*Biodiversité et gestion forestière. Connaître pour préserver,* Synthèse *bibliographique*" and, very recently, the document entitled "*Les coupes à blanc - Une problématique d'actualité du massif du Morvan*" published by Beck *et al.* (2021) in *Cahiers scientifiques du Parc naturel régional du Morvan*, to date the most documented scientific publication on the subject.

The idea of working specifically on the issue of clearcuts arose within the AFORCE Mixed Technology Network[3], where the subject was discussed for the first time at the Network Steering Committee meeting on 28 April 2020. A number of contextual factors came to the fore, in particular the need to address in depth the issue of biodiversity, as well as forest stand renewal in the context of climate change.

The RMT AFORCE network decided to delegate the coordination of the expert assessment to the GIP Ecofor. Back in late 2020/early 2021, this project raised the interest of the ministries in charge of Ecological Transition and Agriculture (MTECT and MASA), ADEME and the OFB, who decided to support

[2] Humanité et Biodiversité, FNE, LPO, UICN, Réserves naturelles de France, WWF
[3] AFORCE is a Mixed Technology network (RMT) designed to support foresters in adapting forests to climate change, while strengthening their mitigation capacities. https://www.reseau-aforce.fr/

the initiative and initiate a co-building phase with the experts, consisting in delimiting the **topics** covered and identifying the **questions** that the Assessment should answer.

It was decided to cover both issues of **clearcutting** and **renewal of forest stands in the context of climate change**, whether or not associated with clearcutting. This means that **natural regeneration** is also taken into consideration.

While the issue of clearcutting has been addressed in a way similar to the Collective Scientific Assessments (EsCO, *Expertises scientifiques collectives*, INRAE, 2021), leveraging mostly scientific knowledge, the issue of forest renewal has been approached by leveraging knowledge from R&D in addition to scientific literature.

This work had the following **objectives**:

- Take stock of the **knowledge gained from scientific research and R&D** on (i) clearcutting and (ii) **renewal of forest stands**. To this purpose, the expert assessment mobilises an extensive multidisciplinary approach.
- Incorporate the **expectations of society** through a user advisory committee.
- Formulate **avenues of improvement** for **forest managers** and more generally, all players in the **forestry & wood industry.**
- Inform **public players** in the subjects addressed.

Implementation and governance of CRREF Assessment

Two main types of approach were used to conduct this expert assessment. Most of the experts' work was based on an **analysis of existing academic literature**, including four meta-analyses[4]. The **'grey' literature** was taken into account throughout the work, mainly in the section devoted to stand renewal. An analysis of regulations and available economic data was necessary to assess the clearcutting practices. The second approach involved conducting five **surveys**, addressed in the section dedicated to renewal.

The topics covered in the report were broken down into some fifty questions, processed by 73 writers and 34 contributors[5] from around twenty public establishments (39% INRAE, 17% ONF, 10% MASA - DRAAF and DSF, 6% CNPF and CNPF-IDF, 4% AgroParisTech, 4% CNPF-IDF, 4% GIP Ecofor, 4% Université de Rouen Normandie, 2% IGN, 2% Université de Pau et des Pays de l'Adour, 13% others[6]) and spread into thematic groups led by experts designated as Theme Leaders.

The drafting work was monitored by the lead experts with back-up from the project team, in charge of an initial joint review of the contribution. On completion of this internal review phase, a second 'external' review circuit was set in motion, similar to the way peer-reviewed journals operate, in order to consolidate the scientific value of the experts' work. A total of 85 external reviews were carried out on all contributions to the assessment (one to three external reviews depending on the text).

The amount of time spent by the experts on the assessment varied greatly: a few hours for the contributors; a week to a month for the writers; up to four months for the lead experts, whose time

[4] A meta-analysis is a systematic scientific method that combines the results of a series of independent studies on a given problem, using a reproducible protocol.
[5] A contributor is defined as any person who has provided information relating to the issue addressed (e.g. dataset, bibliographic selection) but who has not taken part in writing the contribution.
[6] The "Others" category includes the following organisations, each represented by one expert: Académie d'Agriculture de France, Alliance Forêts Bois, ASL Suberaie-Varoise, Bordeaux Sciences Agro, CNES, FCBA, IEFC, Institut Agro Rennes-Angers, OFB, Université Catholique de Louvain, Université de Franche-Comté, Université du Québec en Ouatinais, Université Laval.

was divided between writing their own contributions, monitoring the work of their thematic group and attending meetings.

The CRREF assessment was largely organised according to INRAE recommendations for conducting collective scientific assessments and studies (INRAE, 2021). The CRREF assessment is based on the principle of dedicated committees, as described below.

Project Team

GIP Ecofor was responsible for developing and coordinating the project (scoping, logistical and financial management). The project team, consisting of a project leader (Guy Landmann) and a coordinator (Garance Marquet and later Morgane Delay), was responsible for setting up the group of experts and the users committee (subject to approval by the Steering Committee). The project team was the main contact point for all parties involved in the assessment and was involved in consolidating the assessment findings and disseminating them (organisation of a feedback seminar, publication of final reports).

Steering Committee

The Steering Committee consisted of representatives of the Assessment **funders** (MASA via RMT AFORCE, MTECT, ADEME, OFB) and project team members. Its role was to define the orientations of the project and oversee its implementation. The Steering Committee met seven times during the assessment process.

Users Committee

The Users Committee consisted of **stakeholders from the forestry & wood industry and from civil society**. Its purpose was to inform stakeholders about the orientations and findings of the assessment. It was also a forum for stakeholders to express their views on the assessment (concerns, issues, interests, questions). The opinions of the stakeholders were carefully collected; however, they did not take part in the decisions concerning the project's orientations, nor in the validation of the findings of the expert assessment. The Users Committee met three times.

Key project milestones and deliverables

Launched in March 2021, the first few months of the assessment were devoted to setting up the group of experts. The second major phase of the project was the drafting and review of the contributions. Finally, a **feedback seminar**, open to all, was held on 22 November 2022 at the MASA ministry. The one-day event was divided into two parts: a morning of presentations of the results by the lead experts, and an afternoon of discussion, first in the form of a Q&A session with the lead experts, followed by a panel discussion with representatives of the Users Committee. All presentations and the webcast of the Seminar can be viewed on the GIP Ecofor website[7]. The final months of the assessment process were devoted to the publication of the assessment report and of this summary report.

Structure of Summary Report

This document is divided into seven parts:

General introduction

[7] Go to: http://www.gip-ecofor.org/22-novembre-2022-seminaire-de-restitution-de-lexpertise-collective-expertise-crref-coupes-rases-et-renouvellement-des-peuplements-forestiers-en-contexte-de-changement-climatique/

Part 1 | Definitions

Part 2 | Monitoring clearcuts and assessing their ecological impacts

Part 3 | Historical, social, regulatory and economic analysis

Part 4 | Analysis of renewal methods in the context of climate change

Part 5 | Cross-cutting issues

Conclusions

Parts 1 to 4 consist of summaries of the "long-form" contributions compiled into the full **expert assessment report where each topic is addressed in 5 to 30 pages**.

The **bibliographic references** cited in the texts are listed at the end of the document. A full list of the references used in this study can be found in the full expert assessment report.

Part 1 | Definitions

The *Vocabulaire forestier* glossary (Bastien and Gauberville, 2011) defines a "*coupe rase*" or clearcut as "a single cut covering the entire forest stand and generally preceding its artificial regeneration". This seemingly simple definition contrasts with the diversity of meanings currently found among the various stakeholders. There is a major dividing line between professionals who can agree, albeit with difficulty, on what is and what is not a clearcut, and the general public who understand the term to cover a wider range of cuts, from a landscape, ecological or socio-cultural perspective.

In view of this, a special effort has been made to (1) attempt to define clearcutting in its most varied meanings, and (2) compare this regeneration method with the other main categories of regeneration cuts in forests.

The first question looks at the different approaches - historical, social, silvicultural, ecological, etc. - used by the experts in the CRREF assessment, all of which contribute to the debate on the definition of clearcutting. A second question is intended to place clearcutting in the context of other regeneration methods used in mainland France, and to extend this analysis to the international dimension, particularly in temperate and boreal climates, in a concern for avoiding, as much as possible, any confusion over terminology.

1.1 How to define clearcutting in the forest?

In the absence of a precise, shared definition of clearcutting, we have reviewed its various dimensions, mainly on the basis of the experts' work.

Historically, foresters have been using the French vernacular term "*coupe rase*" (clearcut/clearcutting/clear felling), since World War I, whereas the term "*coupe à blanc-étoc*" had been used in France since at least the King's Ordinance of 1669 to designate a type of tree felling where the trunk is cut a few centimetres above ground, the adjective "*blanc*" (white) referring to the colour of the above-ground part of the stump. Although the term "*blanc-étoc*" originally referred to the tree felling method, the term gradually came to imply the idea of cutting a certain area, whether coppice or high forest.

Society's outlook on the forest has changed a great deal recently, and the term "*coupes rases*" (clearcuts) is now **used commonly** to designate all cuts that "pose a problem" from the standpoint of landscape, ecological or recreational functions, etc. Generally speaking, it involves forestry methods where the vast majority of mature trees have disappeared all at once or over a short period of time. Large-scale or coalescent clearcuts due to successive clearcutting operations within a short time and spatially close to each other are the main cause of most social protests.

Our approach to a **silvicultural definition** is based on a detailed categorisation of the different cuts, based on four criteria:

1) Gradual (as opposed to sudden) disappearance of trees from mature stands,
2) Presence or absence of pre-existing natural regeneration,
3) Permanence (or interruption) of a shrub or grass canopy,
4) Size of the gap created by the cut in the high forest canopy.

These criteria help to differentiate between clearcutting in even-aged high forest, generally followed by planting, and other types of forest stand renewal felling (shelterwood cuts, including final cuts on effective seedlings, coppicing cuts, cutting in uneven-aged high forest, etc.) and unplanned felling (in particular salvage cutting) or felling unrelated to a renewal process (e.g. restoration of open areas). This interpretation leads to a silvicultural definition of clearcutting that is close to the definitions most commonly used today, i.e. "a cut that removes nearly all trees in the stand at once, leaving the ground mostly bare (with no herbaceous or woody vegetation higher than approximately 50 cm) before the stand is regenerated, usually artificially".

Forest inventory and **remote sensing** do not currently make it possible to easily differentiate between a scheduled clearcut and a salvage or coppicing cut, which is a major limitation.

From an **ecological** standpoint, the analysis of microclimatic and biogeochemical criteria us to specify a precise threshold to be proposed for the clearcut area below which there would be no significant disturbance of the forest functioning, but the levels mentioned seem to be well below the 0.5 ha threshold generally used in silviculture as the limit between the even-aged (patches) high forest and the uneven-aged (clumps/groups/gaps) high forest systems. Community ecology criteria also make it impossible to define a simple threshold for clearcutting.

Finally, from a **legal** standpoint, jurists as well as NGOs and the general public may find the proposed silvicultural definition inadequate and could argue that it would be legitimate to adopt a clearer "impact-based" rationale in view of the issues identified in this assessment (see sections 2.2 and 2.3). The challenge would then be to determine whether these impacts are significant, reversible and temporary or on the contrary permanent, and whether or not they require avoidance, impact mitigation or offsetting measures.

The work in this assessment confirms the intrinsic complexity of the subject and the difficulty of satisfying the expectations of the various stakeholders, particularly with regard to an irrefutable definition of clearcutting.

1.2 What are the main types of regeneration cuts in temperate and boreal forests, particularly in mainland France?

Insofar as the clearcut/plantation system - the central focus of this assessment - is only one of a number of **felling methods used for the renewal** of forest stands, it is important to position it in relation to other methods used in mainland France. It is also important to clarify the **terms used** to designate renewal methods in the national and international scientific literature, in order to make the best use of this literature.

Consultation of specialist literature (including Larouche *et al.*, 2013 and Bastien & Gauberville, 2011) and of experts from France (E. Lacombe, AgroParisTech; C. Méredieu, INRAE; and two reviewers) and Quebec (D. Pothier, Université Laval; Ph. Nolet, ISFORT) made it possible to agree on the silvicultural definitions of the main types of regeneration cuts and to situate their use in the main types of silvicultural treatments.

In **mainland France**, we have identified the following main types of renewal cuts (bearing in mind that there are other, less frequent types):

- In high forest system: clearcutting (Figure 1-1), shelterwood regeneration cuts (Figure 1-2), including final cuts on effective seedlings, and irregular cuts (Figure 1-3),
- Coppicing system: simple coppice rejuvenation cuts.

Coppicing with standards combines an even-aged structure (simple coppice) and an unevenaged structure (reserve trees) that can be perpetuated by staddling (marked standards) cuts.

In **other countries**, other types of regeneration cutting are also practised, such as seed-tree regeneration cuts, also called deferment harvest or seed tree system (cuts with reserves used as seed trees), two-age system, cutting with protection of small merchantable stems, and irregular (or delayed, or reserved, or extended, or expending-gap) shelterwood methods.

Tree retention practices for biodiversity preservation, which can be applied to any type of cutting, are also defined.

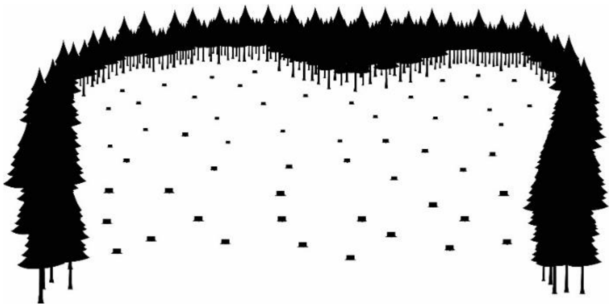


Figure 1-1: Clearcut - All mature trees are removed in a single operation. Diagram RGL Studio

Figure 1-2: Cycle of shelterwood regeneration cuts. From left to right: seedling cut, first secondary cut, second secondary cut, final cut on effective seedlings. Diagram RGL Studio

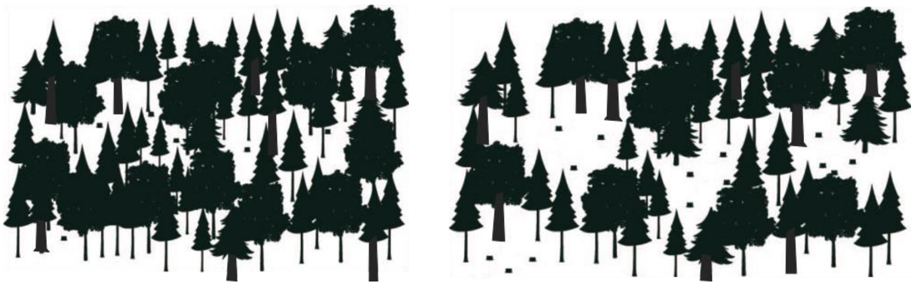


Figure 1-3: Irregular cuts by individual tree (left) or by groups of a few trees (right). Diagram RGL Studio

Part 2 | Monitoring clearcuts and assessing their ecological impacts

This section covers three topics.

The first topic addresses the assessment and monitoring of clearcuts, based on four approaches: (1) updating statistical results by leveraging IFN and ONF datasets, (2) assessing the contribution of space technologies, which have made great strides in recent years both in the design of high-performance satellites and in the processing and use of the data acquired, (3) investigating the implementation of a national system for operational monitoring of clearcutting and heavy felling, benchmarked with (4) initiatives in other countries.

The second area concerns the impact of practices across all factors characterising the physical environment, and if possible beyond the sole clear-cut, the subsequent method of renewal. Six questions are addressed, each analysing a specific aspect of the physical environment: (1) microclimate close to the ground, (2) water regime, at the scale of the forest plot and catchment area, (3) soil erosion, (4) soil fertility and quality of adjacent watercourses, (5) carbon in the soil and (6) physical integrity of the soil.

The third area concerns an in-depth analysis of biodiversity in three parts: (1) Effects of the "clearcutting/renewal system" on biodiversity, at the stand and landscape levels, as the forest succession progresses (i.e. in the short, medium and long term), by comparing, if possible, the effects of clearcutting with those of other regeneration cuts widely practised in France (shelterwood regeneration cuts in even-aged treatment, single-tree or patch regeneration cuts in uneven-aged treatment), with a special focus on the influence of clearcut sizes; (2) Knowledge of the effects of clearcutting depending on the logging practices - retention or removal of slash and stumps, level of soil disturbance including compaction, retention of tree habitats for biodiversity; (3) Effects of clearcutting depending on the practices of post-felling renewal - natural regeneration or planting, with or without preparatory work on the soil, pure or mixed plantations, with indigenous or exotic species. All taxonomic groups were studied, with a focus on soil biodiversity and wild ungulates.

2.1 Knowledge and monitoring of clearcuts

2.1.1. What conclusions can be drawn from national forest inventory data on recent trends in total and partial clearcutting?

Specific work carried out in the **1980s** by the French National Forest Inventory (IFN) had quantified the area undergoing a major change in visual appearance each year at 104,300 ha, of which 35% (36,800 ha) final cuts, completing the cycle of shelterwood natural regeneration cuts in even-aged high forest, and coppicing cuts, 30% (31,100 ha) clearcutting, and 4% (4,200 ha) various other types of felling, in addition to 17% (17,300 ha) ‘heavy’ felling (removing 50% to 90% of the canopy) and 14% (14,900 ha) land clearing cuts (Barthod *et al.*, 1999). The average unit size of clearcut areas at the time was 4.4 hectares.

Since 2005, the IFN has recorded the presence of clearcuts under 5 years old on each of its inventory plots (around 6,000 plots of 0.2 ha each year) and the proportion of the initial overstorey trees that they represent. An objective definition and a precise protocol are used by field operators without seeking to determine the associated silvicultural management. An analysis of these data shows that the level of “clear and heavy” felling (disappearance of at least 50% of the overstorey trees) for the recent period (2011-2020) is comparable (93,000 ha/year ±7,000 ha/year) to the level recorded in the

1980s. Cutting of over 90% of the overstorey trees (corresponding to clearcutting, part of the final cuts and various other cuts including coppicing) amounts to 67,000 ha/year ±6,000 ha/year. The levels of annual felling of over 90% of the overstorey trees show sharp contrasts between regions, depending on whether the forestry management includes clearcutting as the main regeneration method and concerns short rotation species (e.g. maritime pine in Nouvelle-Aquitaine) or, on the contrary, whether the even-aged high forest is less dominant (due to the importance of the coppice/high forest mix and of the uneven-aged high forest) and concerns longer rotation species (e.g. oak, beech, in the Grand-Est region). The very low rates may also reflect the fact that no forestry operations have been carried out for many years (e.g. Corsica).

The proportion of forests where more than 90% of the overstorey has been cut is highest for private forests with a simple management plan (PSG) (Figure 2-1).

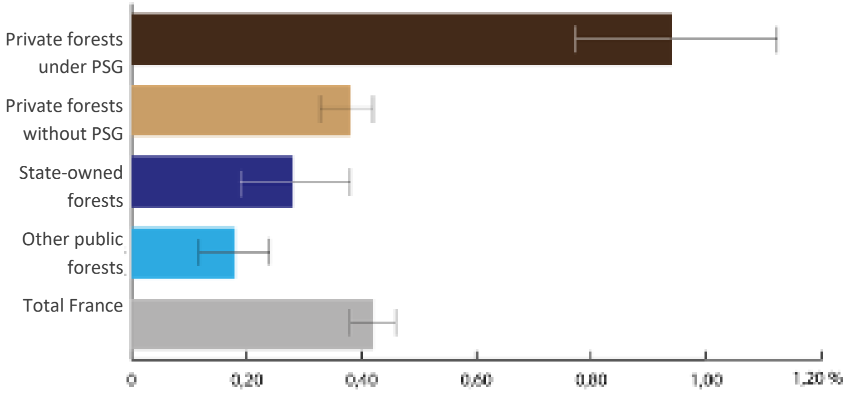


Figure 2--1: Proportion of annual clearcuts exceeding 90% of the overstorey in the total production forest area - 2011-2020 period

The species most frequently felled in clearcuts exceeding 90% of the overstorey are maritime pine, chestnut, common spruce and cultivated poplar (Figure 2-2).

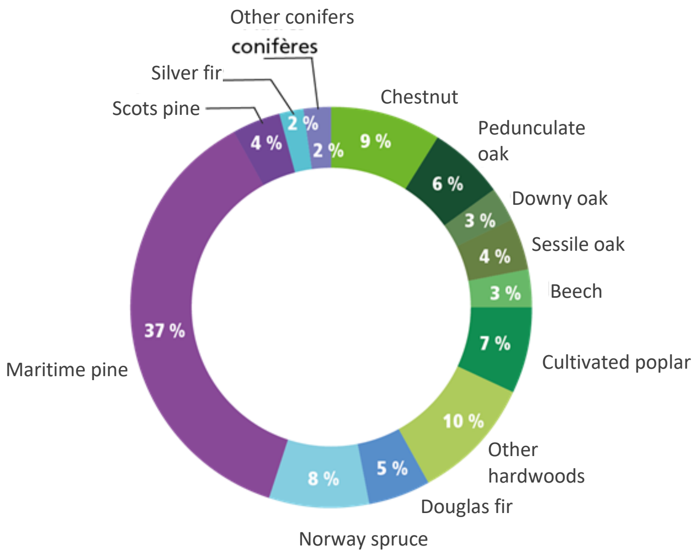


Figure 2-2: Breakdown by species of the surface area of cuts exceeding 90% of the overstorey

The proportion of these cuts linked to plant health problems cannot be determined using this approach. Between 1980 and 2010, the proportion of cuts exceeding 90% of the overstorey trees in forests managed under the public forestry system[8] fell sharply compared with private forests.

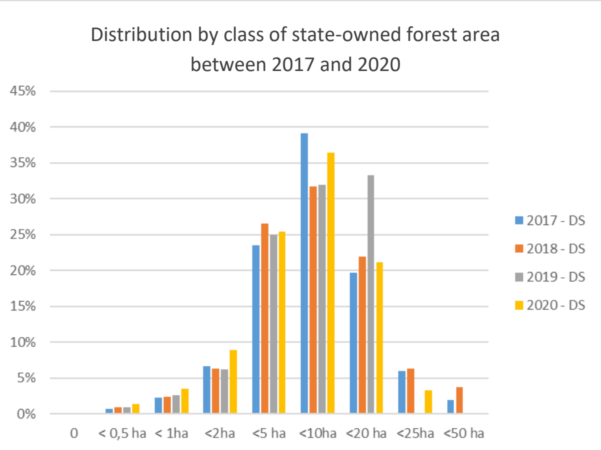
2.1.2 What lessons can be drawn from the ONF's operational data on clearcuts?

The ONF's **operations for designating stems to be harvested** enable various data to be entered for each cut implemented in forest management. This data has been available in a **database** since 2017. In particular, the surface areas covered are known for each type of cut, especially for **clearcuts** and **sanitation cuts**. The different types of felling have been analysed by type of property (state-owned, local authority) and by type of stand in order to put into perspective the proportion of clearcuts in the total felling carried out and their size distribution for the period 2017 to 2020.

For all annual cuttings, clearcuts (including sanitation cuts) are carried out at a low level, accounting for just over 1% of the total areas studied. This type of felling accounts for 10% of the areas renewed, with the major proportion renewed by natural regeneration. This level observed in a normal year (2017) from a health standpoint, has increased in 4 years due to clearcutting carried out for sanitation reasons.

The largest increases in clearcutting during the recent dry period, associated with **bark beetle attacks**, concerned mainly spruce stands. The average surface area of clearcuts has tended to decrease over those 4 years, with a lower rate in local community-owned forests (2.9 ha) compared with state-owned forests (4.5 ha), a difference linked to the larger average size of plots in state-owned forests. These differences are also reflected in the distributions by surface area class between the two types of ownership.

To sum up, clearcutting, as understood by public forest managers, is a relatively small proportion of the so-called regeneration cuts. The upward trends seen in recent years are linked to health problems. The size of clearcuts has not increased in this health control context. These management data are difficult to reconcile with IGN data for methodological reasons, but the orders of magnitude are fairly consistent.



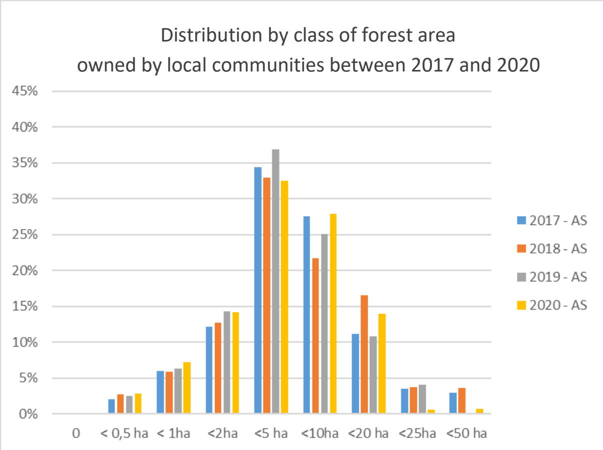


Figure 2-3: Changes in the size of clearcuts in state- and local community-owned forests. Distribution by area class over the period 2017-2020

[8] Forests belonging to the State, to local authorities (communes or, more rarely, departments or regions) or to public establishments or charitable institutions.

2.1.3 How can satellite imagery contribute to clearcuts monitoring?

Space-based Earth observation systems date back to the 1970s. The recent development of platforms and sensors with increasingly high resolution - in spectral, temporal and spatial terms - and the definition of new methods of analysis are considerable. The data extracted enable changes in surface condition to be detected, although they still need to be validated by experts in order to accurately characterise silvicultural practices or other phenomena involved.

The methods described here are based on the analysis of time series of satellite, optical and radar images. INRAE provides government agencies with **maps of sudden changes in vegetation indices** (Figure 2-4) **derived from optical images acquired by the Sentinel-2 constellation** (10 m spatial resolution). These data are intended to help operators draw up their plans for controlling cuts that reveal faulty declarations not complying with an area threshold set at Department level (articles L124-5, L312-9, L312-10, R312-19 to 21 of the Forestry Code: illegal felling, abusive felling and restoration after felling (L124-6)). As part of this assessment, the data were statistically processed and cross-referenced with IGN data in order to estimate losses of woodland cover over the period 2017-2020 according to categories of ownership, single-block surface area, and stand type. CESBIO, in partnership with Globeo, is developing methods based on radar imagery from the Sentinel-1 constellation to track deforestation events more accurately in intertropical zones where cloud cover prevents routine use of optical systems. A study is currently underway to transpose these methodological approaches to a temperate context. Finally, the Nouvelle-Aquitaine DRAAF presented a protocol established in 2012, combining remote sensing with its own data (forest ownership, simple management plans, felling or land clearing declarations, etc.) to improve the quality of clearcuts mapping throughout the region.

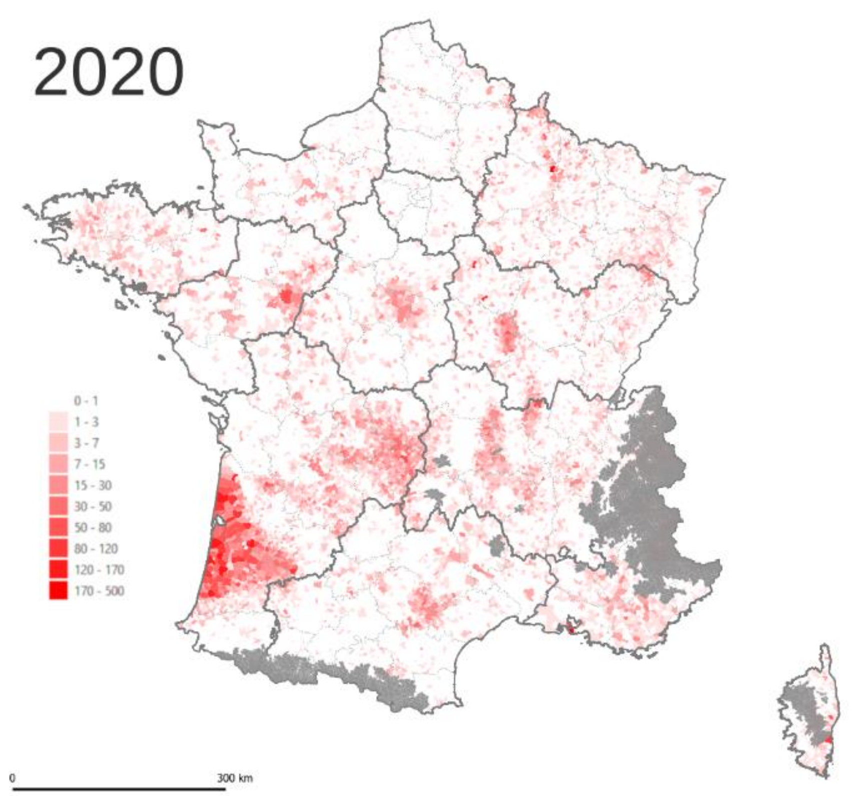


Figure 2-4: Tree cover losses in 2020, expressed in hectares per municipality (INRAE method) (Municipalities situated wholly or partly above 1600 m altitude are shaded in grey because detection is subject to greater uncertainty).

Satellite monitoring of tree cover loss with a single sensor (Sentinel-1 or Sentinel-2) very rarely differentiates between types of removal; the statistics derived generally include forest felling, whatever the purpose, but also damage due to storms, fires and any other phytosanitary problem. Rates of tree cover loss calculated using databases derived from satellite imagery (UMD-GLAD **internationally**, INRAE **nationally**) should be interpreted with caution and circumspection. At national level, the statistics extracted since 2017 from the UMD-GLAD and INRAE databases are very similar. They show that the estimated loss of tree cover is relatively constant, ranging from 70,000 to 80,000 ha depending on the year. There is however less consistency at the regional and lower scales. The Departments that stand out the most, both in terms of surface area and number of plots, are Les Landes, Gironde and Corrèze in the **Nouvelle-Aquitaine** region. At local level, the DRAAF Nouvelle-Aquitaine has chosen to adapt remote sensing methods and carry out exhaustive photo-interpretation checks, in order to produce maps useful in an operational context. In particular, these maps help to optimise controls, but also to estimate the annual requirements for pine seeds to replenish harvested areas.

2.1.4 What could be the objective and components of an operational system of regular monitoring of clearcutting and heavy cutting in mainland France?

In France, there are a number of systems for monitoring clearcuts or 'heavy' cuts. These systems are based on different methods and pursue different goals (inventory, operational monitoring, initial diagnosis for government administrations). As a result, their strengths and weaknesses are equally diverse. Some operational systems are based on observations made in the field (national forest inventory, ONF monitoring of felling in public forests), while others are based on remote sensing and satellite image processing, such as the INRAE mapping of sudden forest cover loss, and the Hansen map of forest cover losses and gains (Hansen *et al.*, 2013).

It is possible to develop an **operational monitoring method** backed simultaneously by previously tried and tested systems, since their strengths and weaknesses are highly complementary. This monitoring will have to mobilise simultaneously (i) field observations because of their precision in terms of felling typology, with firstly IGN forest inventory data, and (ii) maps obtained using remote sensing such as the INRAE method which provides rich spatial and temporal information, while constantly seeking to improve these systems based on ongoing research.

Lastly, a broader system for **disseminating the results** needs to be put in place, as the current results from national systems are difficult to access by a wide audience, unlike the Hansen map for instance that is accessible on the Global Forest Watch platform. This will necessarily be backed by a review of ways for non-expert users to access information, support for this information and its integration into a reliable and controlled national "information dissemination system". The linkage with the IGN Forest Observatory currently being developed and the Theia continental surface cluster will need to be defined.

2.1.5 What is the current status of global warning systems using satellite-enabled remote sensing?

Forest Alert (FA) **systems** using satellite remote sensing provide maps to measure deforestation. As it stands, the issue of clearcutting is not really addressed, but clearcuts are detected together with the other types of disturbance that cause deforestation.

Several government organisations and research institutions have developed operational systems, based mainly on **optical remote sensing** data. With a coarse spatial resolution (images with 250 m spatial resolution), the Forest Monitoring for Action, Terra-I and Forest and Carbon Monitoring systems were developed in 2012-2014 to monitor deforestation from the national scale (IDEAM for Colombia) up to the pantropical scale. They provide bi-weekly, monthly and quarterly data respectively. Near real-time deforestation detection (DETER-B) is an operational Brazilian system, developed by the Brazilian space agency (Instituto Nacional de Pesquisas Espaciais, INPE), which monitors forests at a spatial resolution of 60 m and a frequency of 5 days. Peru's Ministry of the Environment (MINAM) and the University of Maryland (UMD) generate weekly FA systems using medium-resolution (30m) images acquired by Landsat satellites. This involves the Early Warning System of the Programa Nacional de Conservación de Bosques (PNCB) and the Global Land Analysis and Discovery (GLAD) system known as Forest Alert. Recent alerts from the GLAD-Forest Alert system are available on the Global Forest Watch web platform. Operational deforestation detection systems have emerged recently, based on **radar remote sensing** data for tropical forests using Sentinel-1 satellite images at 10m spatial resolution (RADD system developed by Wageningen University, available on Global Forest Watch and TropiSCO system developed by Cesbio-CNES-Globeo, available on www.tropisco.org). The main advantage of these methods is their ability to detect cuts in cloudy conditions (important when detection is used for warning purposes, as in Brazil).

At **European level**, there is no operational monitoring system for all forests in the EU, but the new EU forestry strategy for 2030 states that the European Commission will present a legislative proposal on a framework for forest observation using remote sensing technologies, among other.

2.2 Effects on the physical environment

2.2.1 What is the impact of clearcutting (or other types of cuts) on the microclimate?

By creating openings in the canopy, forest felling increases radiative and thermal exchanges near the ground compared with an unharvested stand, and thus greatly modifies the **forest microclimate**. This impact has been known for many years, as it affects the development of seedlings and saplings, depending on their tolerance to shade, sub-zero temperatures, heatwaves, drought or strong winds. In the increasingly pressing context of climate change, research on the impact of forest management on the microclimate is attracting new interest, because mitigating climatic extremes in the undergrowth has an impact not only on the dynamics of regeneration, but also on a range of ecosystem services provided by forests, such as maintaining biodiversity or storing carbon belowground.

Generally speaking, clearcutting increases solar radiation on the ground in daytime, but also radiative losses at night, which raises the daily and seasonal amplitudes of air temperatures of air close to the ground and at the soil surface (Aussenac 2000; Figure 2-.A). Clearcutting also increases surface wind speed. It increases soil moisture, except at the soil surface that tends to dry out more quickly, an effect that diminishes with spontaneous vegetation regrowth but can last for several years.

For **small-size cuts** (gaps, typically <0.25 ha), the effect on microclimate is marked mostly for extreme values of temperature or humidity, and does not always increase with the size of the gaps; for example, soil moisture at the end of summer is higher in small natural gaps than in larger gaps or uncut areas.

Microclimatic variations also occur within and at the **edge of clearcuts**, up to 100 m for certain microclimate variables (air temperature or moisture, Figure 2-.A), and are generally greater on the southern boundaries or at the edge of sparsely forested areas.

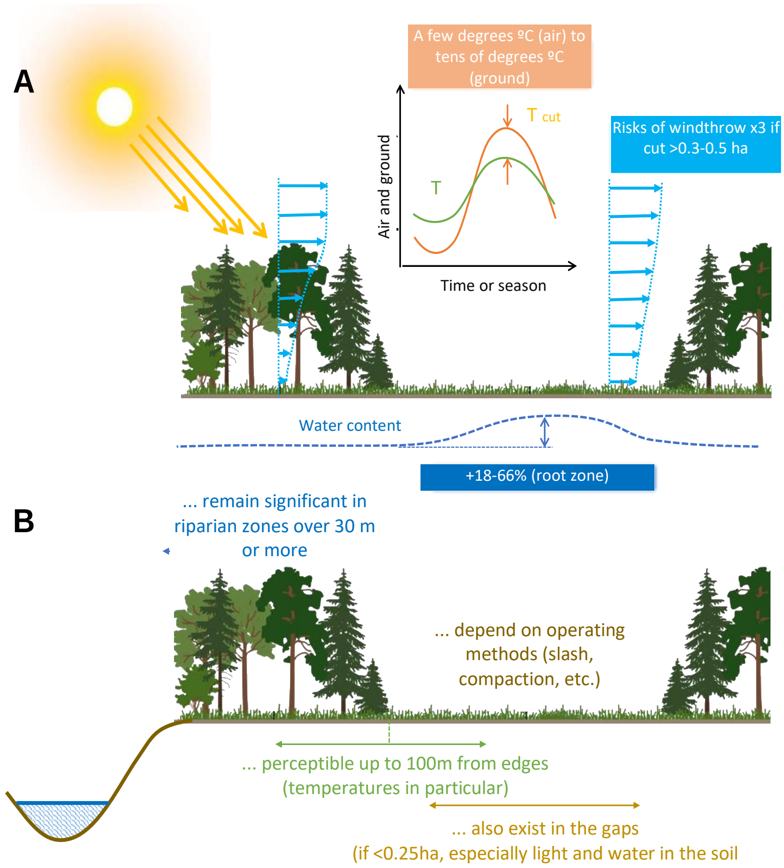


Figure 2-5: Impact of clearcutting on the near-ground microclimate (A) within the cut and (B) beyond the cut, or depending on operating methods or size of the cut.

The microclimate on the **banks of a river** close to a clearcut is altered for several years, even if the newly created edge is several tens of metres from the watercourse.

Even for species known as shade intolerant, some studies have highlighted the existence of an **optimum cut size** for the survival and growth of juveniles that optimises their needs for light, water and nutrients. This optimum cut size varies according to the species, herbaceous competition, herbivore pressure, and age, but generally remains small (<0.25ha).

When the gap size is greater than two to three times the tree height, the **risk of windthrow** during storms increases considerably, around threefold.

Finally, **very large clearcuts** (>10,000 ha) (e.g. sanitation clearcuts after extreme storms in the French context) can also modify the regional climate due to a sudden change in leaf area index, albedo or roughness, the combination of which can lead to an increase or decrease in cloud cover and rainfall depending on water availability.

2.2.2 What is the impact of clearcutting on the water balance components of the forest ecosystem?

Interactions between forests and the continental water cycle have long been acknowledged. By removing the tree layer, clearcutting has an impact on several components of the **hydrological cycle**, at the stand scale as well as at the landscape scale.

A recent summary of findings from 155 catchment areas quantified the increase in **runoff** and **erosion** (sediment transport) at 47% and 700% respectively following clearcutting. These effects of clearcuts are mainly due to the reduction in **evapotranspiration** and to a modification of the **hydrodynamic properties of the soil**. Clearcutting reduces evapotranspiration by abruptly eliminating tree transpiration, but also by reducing the evaporation of rainwater intercepted by the crowns. This reduction is greater for conifers (65%) than for broadleaved trees (around 37%). In the 3 to 5 years following felling, the reduction in transpiration averages 12% in boreal forests and 23% in temperate forests, and the drop in evapotranspiration varies from 14% in boreal environments to almost 50% in temperate environments.

The hydrodynamic properties of forest soils are strongly affected by the **forestry operations** associated to clearcutting. Soil macroporosity can be reduced from a few percents in dry soil to over 50% in moist soil. Hydraulic conductivity is reduced by up to 77% in moist soils and by only 3 to 6% in dry soils, with wide variations depending on soil texture. The nature and weight of the vehicles and their undercarriage, tyres or tracks, as well as the state of the ground at the time of operations - dry, moist or saturated - are the major factors explaining the variability of these effects.

The reduction in evapotranspiration also leads to an increase of water content in the soil (10 to 66% on average over a soil thickness of 25 to 50 cm) and a **rise in the water table** of up to several tens of centimetres. This rise in water table level is observed primarily near the median depth of its natural fluctuations. In mountainous and boreal regions, flash floods are also more frequent in clearcut areas because of increased run-off due to lower soil permeability and reduced evapotranspiration.

The hydrological effects of clearcutting also have a major impact on water and energy balances at a **regional scale**. In fact, the reduction in energy exchanges through evaporation is generally accompanied by an increase in radiative exchanges, and these changes have repercussions on atmospheric moisture and heat flows between continental surfaces and the atmosphere.

2.2.3 Does clearcutting increase the risk of soil erosion?

Plant cover, particularly woodlands, with its deep root system and foliage that reduces wind and run-off, plays a fundamental role in slope stability and reducing soil erosion. Clearcutting disrupts this **protective role of the surface layers of the ground**, to an extent that depends on a number of factors (slope, rainfall, etc.).

Clearcutting increases the risk of soil erosion, mainly for two reasons: (i) the **sudden disappearance of the forest canopy** reduces the interception of rainfall by the vegetation, and (ii) the **soil compaction** caused by the passage of machinery during timber harvesting limits water infiltration. This reduction in rainwater interception and infiltration potentially leads to more run-off, and therefore more erosion.

In such situations, erosion rates after clearcutting are often well above the values that guarantee soil sustainability and will continue for several years. If the sediments produced are not trapped (presence of an unexploited area downstream), the sediments reach the river system and disturb this environment. As one might expect, erosion increases due to clearcut areas, often with irreversible consequences.

2.2.4 What is the impact of clearcutting on the chemical fertility of soils and the chemical quality of surface water?

In forests, the chemical fertility of soils is based on the soil's reservoir of nutrients, but also on the circulation and recycling of elements specific to biogeochemical cycles. By causing in particular the **removal of biomass**, an **abrupt break in the biological cycle** and **changes to the pedoclimate**, clearcutting constitutes by nature a significant disturbance of the **chemical fertility of the soil** and the

chemical quality of surface water. The temporal evolution of these indicators after felling should also be investigated in order to assess the duration of the effects observed.

The chemical fertility of soils is impacted first and foremost by the harvesting of biomass associated with clearcutting, which represents a net loss for the soil's carbon and nutrient reserves: retention of roots, woody debris and especially foliage (everything referred to as slash) can limit the removal of elements, thus preserving chemical fertility.

Clearcutting generally leads to increased concentrations of ammonium, nitrate and major cations (Ca, Mg, K, Al) in **soil solutions** in the years following the cut. As nitrate molecules are negatively charged (NO^{3-}), they are necessarily accompanied (for charge equilibrium) by positively charged ions: generally major alkali and alkaline-earth cations (Ca^{2+}, Mg^{2+}, K^{+}) and/or aluminium (Al^{3+}) in acidic systems with a low alkali and alkaline-earth cation content. These concomitant increases reflect a soil acidification mechanism that can lead to a more or less rapid desaturation of the exchange complex, depending in particular on the soil's buffering capacity: most of the studies reviewed show a decrease in concentrations and/or stocks of exchangeable nutrient cations (Ca, Mg, K) in the soil, as well as a drop in total nitrogen stocks in the years following clearcutting, indicating a loss of chemical fertility.

Watercourses downstream of harvested areas generally show an increase in nitrate and major cation concentrations (Ca, Mg, K, Al). Calcium, magnesium and potassium removed from the soil by drainage improve the chemical quality of the watercourse, but this is not the case for aluminium (Al^{3+}), which is toxic to living organisms; in these situations, the chemical quality of the water is severely degraded.

The duration of the effects observed on soil solutions and watercourses is generally less than or equal to 5 years, with a maximum effect in the first two to three years after felling, followed by a gradual return to pre-felling conditions. Stocks or concentrations of exchangeable nutrient cations, bioavailable phosphorus and total nitrogen in the soil generally decline in the years following clearcutting. The literature also reports later responses and/or a longer duration of effects, sometimes approaching and even exceeding a decade.

2.2.5 Does the clearcutting/renewal system cause major carbon losses in the soil?

Forest ecosystems mitigate climate change because of their ability to sequester atmospheric **carbon** (C) in woody biomass, but also and above all in the form of **organic carbon in the soil** (Jonard *et al*., 2017). Forest soils currently accumulate an average of 0.35 tC/ha/year, with total storage up to 100 tC/ha in French continental forests (Pellerin *et al*., 2019). In total, the stock of organic carbon in the soil and in the biomass of forests in mainland France is estimated at 2,826 MtC, equivalent to the country's greenhouse gas emissions over the last 20 years. The C stock in forest soils represents 51% of this total (ADEME, 2021) and is less exposed to hazards (fires, droughts, storms, pests, diseases, etc.) than the stock stored in biomass. The stand renewal phase, and more specifically clearcutting, disrupts C stocks and, more generally, the functioning of forest soils (Mayer *et al.*, 2020); the biogeochemical carbon cycle is closely coupled to the cycles of nutrients such as nitrogen and phosphorus, which gives soil carbon a pivotal role in tree nutrition and therefore in maintaining forest productivity.

With regard to felling involving only the **harvesting of merchantable timber**[9], clearcutting as such (i.e. the harvesting of all trees, without taking into account any associated operations such as tillage) does not significantly affect soil properties such as pH or bulk density (apart from traffic paths). However, these cuts have a significant impact on soil carbon levels, which can last for one or more decades, with

[9] Which only takes into account wood with a minimum diameter over 7 cm.

an increase in carbon stocks in woody debris (+7%), accompanied by a sharp fall in litter (-28%) and the surface soil layer (-10% Figure 2-, Figure 2-6. A).

While changes in the deeper layers vary greatly depending on the context, but are on average insignificant, the losses observed at the top of the soil profile correspond to around 5-7% of the soil's total organic carbon stock, with major disparities from one site to another.

Carbon losses are observed to increase with the scale of management operations (Achat *et al.*, 2015a). Soil carbon losses are highest after **harvesting whole trees** and **stumps** (Augusto *et al.*, 2022). On nutrient-poor sites, this could have serious consequences for fertility (see

2.2.4 What is the impact of clearcutting on the chemical fertility of soils and the chemical quality of surface water?), productivity and long-term carbon sequestration (Achat *et al.*, 2015b). Similarly, carbon losses due to clearcutting are around twice as high when the top soil layer has been mechanically **prepared**: on average -21% with preparation compared with -9% without.

Finally, the extent of the changes in soil C stocks varies significantly with the soil and climate context; the warmer the **climate** and the finer the **texture** of the soil, the more pronounced the changes (Figure 2-B).

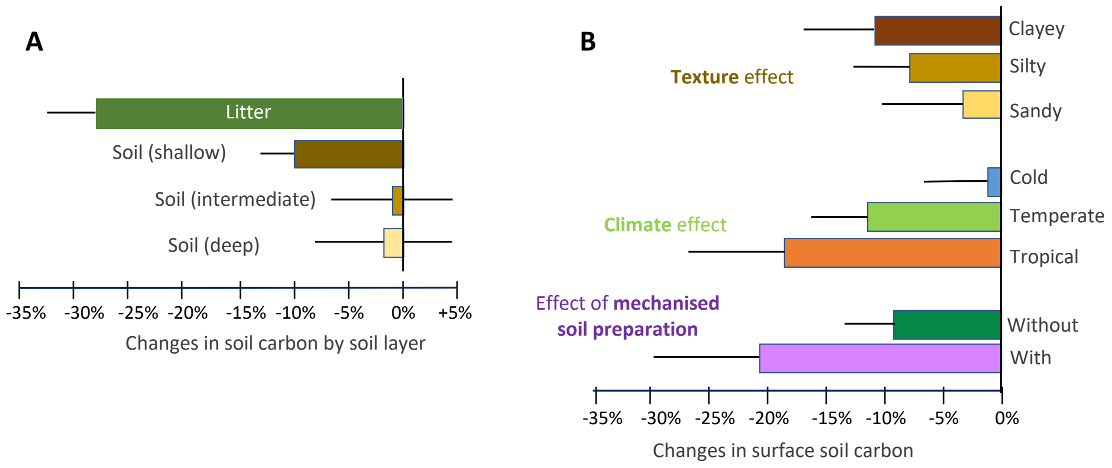


Figure 2-6: Average observed effects of clearcutting on soil carbon loss (A) by horizon and (B) according to soil and climate conditions and soil preparation.

2.2.6 What is the impact of clearcutting on the physical integrity of soils?

Forestry operations are generally carried out by land access, which involves a **risk of soil compaction due to the machinery traffic**. This compaction modifies the physical integrity of the soil by altering its structure: mixing of organic and mineral horizons, increased bulk density[10], reduced porosity. The empty spaces between solid particles are necessary for roots and living organisms to penetrate and for water and air to circulate.

Clearcutting degrades the soil structure as a result of machinery traffic. The large **volumes harvested and transported**, as well as the absence of **road markings**, increase the risk of soil compaction during clearcutting compared with other types of felling.

[10] Bulk density is the **mass of soil present in a given volume, generally expressed in g/cm3**

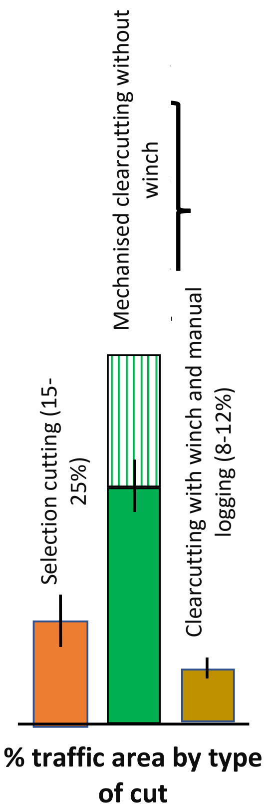


Figure 2-7: Traffic area by type of cut

Virtually all the publications reviewed show that effects on the physical integrity of soils are very high for the different types of land-based harvesting and very low for operations without traffic on the cutover (Picchio *et al.*, 2018), i.e. by **cable yarder** or **cable skidder** (Figure 2-2-7). This deterioration in soil structure after clearcutting can be observed from the first machinery passes across the cutover; it hinders the rooting of seedlings and reduces water and air transfers into the ground (Mariotti *et al.*, 2020). The reduction in soil aeration caused by machinery traffic slows down the activity of roots and of a large proportion of organisms living in the soil (all aerobic organisms). It can lead to the decline of stands sensitive to the lack of oxygen, and to plantation failures.

Finally, the reduced transfer of water to the soil resulting from machinery traffic increases the **risk of temporary waterlogging** at the surface (in lowlands) or **run-off** and **erosion** (on slopes) and increases the risk of **soil drought** if the water no longer reaches the deeper horizons.

2.3 Effects on biodiversity

2.3.1 What are the impacts of the different categories of forest regeneration felling on biodiversity (at stand scale)?

Clearcutting is one type of regeneration cuts among others. These cuts differ in the size of the gaps they create in the forest canopy and whether or not vegetation and trees are left on the cutover area. Based on an in-depth literature review - meta-analysis coupled with a qualitative review - based on the work of Duguid & Ashton (2013), Chaudhary *et al*. (2016), Nolet *et al.* (2018), Basile *et al.* (2019), Savilaakso *et al.* (2021), Forsman *et al.* (2010) and Nascimbene *et al.* (2013), we compared the **effects of the main types of regeneration felling in high forest** (clearcutting and shelterwood cutting in even-aged treatment, single-tree cutting or patch cutting in uneven-aged treatment) on biodiversity at stand scale, in the **short** (<20 years), **medium** (20-50 years) and **long term** (>50 years), compared with an uncut or naturally evolving control stand.

In even-aged stands resulting from clearcutting or shelterwood cutting, a short-term increase is noted in the number of species, all taxa considered followed in the medium term by a gradual decrease, leading in the long term to stands with a lower species richness than the control stands. These effects vary according to the taxa and ecological groups of species; short-term enrichment mainly concerns open-habitat species, while in the medium and long term, impoverishment is particularly high for mature-stand forest specialist species (Figure 2-8). Consequently, even after 50 years, a mature stand resulting from clearcutting or shelterwood cutting is poorer in specialist forest species than an uncut control.

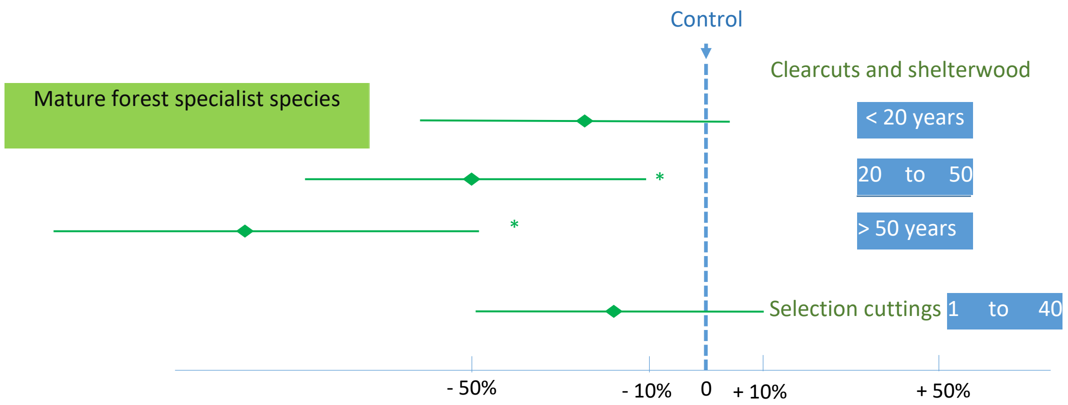


Figure 2-8: Results of a meta-analysis on the short (<20 years), medium (20-50 years) or long-term (>50 years) effects of clearcutting or shelterwood cutting (1 to 40 years after cutting) on the richness of mature-stand forest specialist species (all taxa), compared with an uncut or freely evolving control. * Significant effects ($p < 0.05$). Diamonds indicate the mean value of the estimators and solid lines show the 95% confidence interval.

Compared with clearcuts, shelterwood cut stands tend to have more species, but this is a non-significant trend, insufficient to avoid negative long-term effects.

In uneven-aged treatment, felling does not significantly affect local species richness, whether in the short, medium or long term, for all taxa combined or for mature forest specialist species, despite a (non-significant) trend towards more species in the short term and fewer forest specialist species in the long term.

2.3.2 What are the effects of clearcutting on soil biodiversity, compared with partial cutting?

This section focuses on soil biodiversity, i.e. microbial (viruses, bacteria, fungi) and faunistic (micro-, meso- and macro-fauna) communities living in or at the surface of soils. It is based on a qualitative review of the literature, which mainly looked at studies of softwood forests in North America and Fennoscandia, and a few studies of temperate forests.

Microbial communities (Marshall *et al.*, 2000; Chen *et al.*, 2021; Bowd *et al.*, 2022): In the short term, until stand closure, clearcutting leads to an overall reduction in microbial biomass, with a subsequent increase in nitrogen mineralisation. **Fungal communities** are the most affected: They decline in richness and abundance, and their composition is modified, with a sharp drop in ectomychorizae (EcM), essential for tree nutrition, and an increase in arbuscular mychorizae (linked to herbaceous plants) and saprotrophs. A reduced EcM number is also observed after shelterwood cutting. The composition of **bacterial communities** is modified and becomes spatially homogenised. After closure of the stand, 30 to 60 years after felling, the communities return to their pre-felling composition, with the exception of a few less frequent species.

The proximity of forest edges and woody regrowth fosters root colonisation by EcMs. Depending on the context, the retention of habitat trees (see 2.3.7 Retention methods) can have either positive effects (increasing with the retention rate, and more so with aggregate-tree retention), or no effect at all.

Faunistic communities: In Northern Europe, negative effects on soil fauna are observed from the moment a cut removes more than 33% by volume, and retention practices mitigate the negative effect of clearcuts (Gustafsson *et al.*, 2010). For macrofauna, clearcutting leads to an overall reduction in the abundance of predators in the short and medium term (10-12 years) (particularly arthropods and arachnids) and, to a lesser extent, herbivorous and fungivorous arthropods; it has no effect on the abundance of detritivores. It has no negative effect on species richness, but the composition of communities is significantly altered: more open-habitat species, fewer forest specialist species. These effects fade over the long term. Abundance and richness of the mesofauna (springtails, oribatid mites and enchytraeids) depend entirely on the type of forest: in boreal coniferous forests, clearcutting has no effect or a favourable effect; in broadleaved forests (temperate or boreal), clearcuts or partial cuts have either no effect or on the contrary negative effects.

2.3.3 What is the impact of clearcutting on biodiversity at landscape level?

Clearcutting changes the composition and structure of the **landscape mosaic**, i.e. the variety of habitats present and their spatial pattern. Clearcutting can have effects on biodiversity beyond the boundaries of the cut area, both on the adjacent forest (through an edge effect) and on a wider scale (due to a fragmentation of closed-canopy stands and to biotic exchanges between habitats that make up the landscape mosaic).

The effects of clearcutting on biodiversity at landscape level were assessed on the basis of a literature review or meta-analysis, addressing the following questions:

- What is the edge effect on biodiversity between a clearcut and adjacent stands?
- What is the effect of size (addressed by meta-analysis), quantity and spatial layout of clearcuts on a wider landscape scale?
- Can clearcuts be a replacement habitat for open habitat species?

The **edge effect** is well documented (Baker *et al.*, 2013; Franklin *et al*., 2021). Generally speaking, it amplifies the local effect of clearcutting, with a decline in forest species and a penetration of non-forest species into the forest interior (Figure 2-9). Alternatively, a peak in abundance or richness at the edge may be observed for certain species or taxonomic groups (birds, mammals, ungulates, Figure 2-9). The edge effect acts in both directions (from the clearcut to the adjacent stand and vice versa) and varies with age since the clearcut (Baker *et al*., 2013). Thus, the forest species recolonise the clearcut area a few years to several decades after the felling. The edge effect of clearcutting can range from a few metres up to 200 m and may vary depending on the size of the cutover and the type of adjacent stand.

B- Positive edge effect

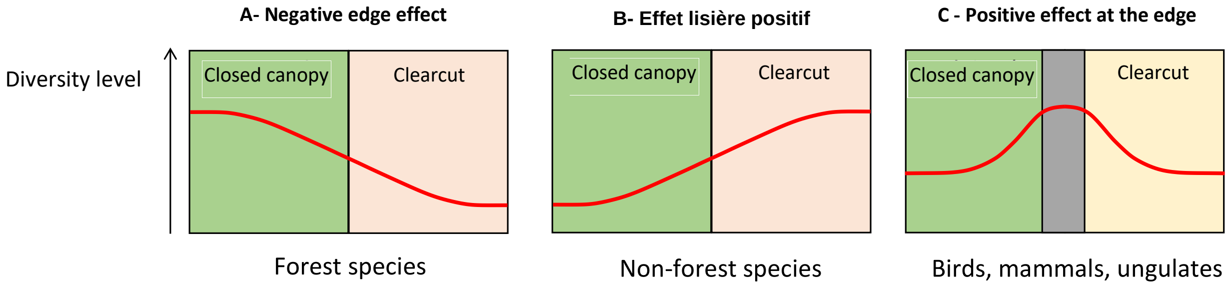


Figure 2-9: Biodiversity response profiles to the edge effect between a clearcut and an adjacent uncut forest stand: negative edge effect for forest species (A), positive for non-forest species (B), peak in diversity at the edge between the two habitats observed for certain species or taxonomic groups (C).

Regarding the effect of **clearcut size**, based on the current state-of-the-art published studies, our meta-analysis indicates that clearcut areas of less than 10 hectares have no negative effects on the specific richness or diversity of insects, birds and vascular plants.

The effects of **quantity** and **spatial distribution of clearcuts** on the landscape are only moderately documented. The only evidence based result is that clearcutting has a highly negative effect on the biodiversity of forests located along watercourses, with a range of up to 100 m. Furthermore, the amount of clearcutting in the landscape has variable effects depending on the taxon and the context. Conversely, the question of the spatial distribution of clearcuts has not been explored, and it is difficult to conclude whether it is better to concentrate felling in a small number of large clearcuts or to spread them out over a large number of small clearcuts.

Several studies have highlighted the fact that clearcutting in forest landscapes can help to conserve **open –habitat species** (birds, insects and plants, including protected species), which may be in sharp decline in regions where agriculture has intensified and semi-natural grasslands have declined sharply (Ram *et al.*, 2020).

2.3.4 What is the impact of open areas after disturbances such as regeneration cuts (including clearcuts), storms, epidemics and fires on populations of large wild ungulates?

Populations of wild ungulates have risen sharply in Europe in recent decades, leading to regeneration failures in situations of overabundance and impacts on the dynamics of forest vegetation, which determines the presence of other taxa. A partial review of the literature has however shown that clearcuts are likely to stimulate the growth of herbivorous ungulate populations and to modify their spatial distribution, and with what consequences for floristic diversity or other taxa. Gaps due to storms, epidemics or fires were regarded as similar to openings from clearcuts.

The young stands that follow regeneration cuts or post-disturbance gaps are largely selected by herbivorous ungulates for the abundance and quality of the food resources they find there. But **food supply** is not the only factor influencing the behaviour of these ungulates who seek to limit their **movements** when feeding and maximise energy gains while minimising the risk of predation. They therefore prefer small regeneration patches (<0.5 ha) which allow them to reduce the size of their home range.

By providing abundant and palatable food resources, clearcuts (>1 ha), like natural post-disturbance gaps, can also stimulate the growth of herbivorous ungulate populations. But the larger the cutover area, the more a vigilance behaviour increases at the expense of foraging time. In this case, it is presumed that browsing pressure is lower.

These changes in the spatial distribution of ungulates can have consequences for floristic communities (via the mechanisms of herbivory and zoochory) - Figure 2-10.

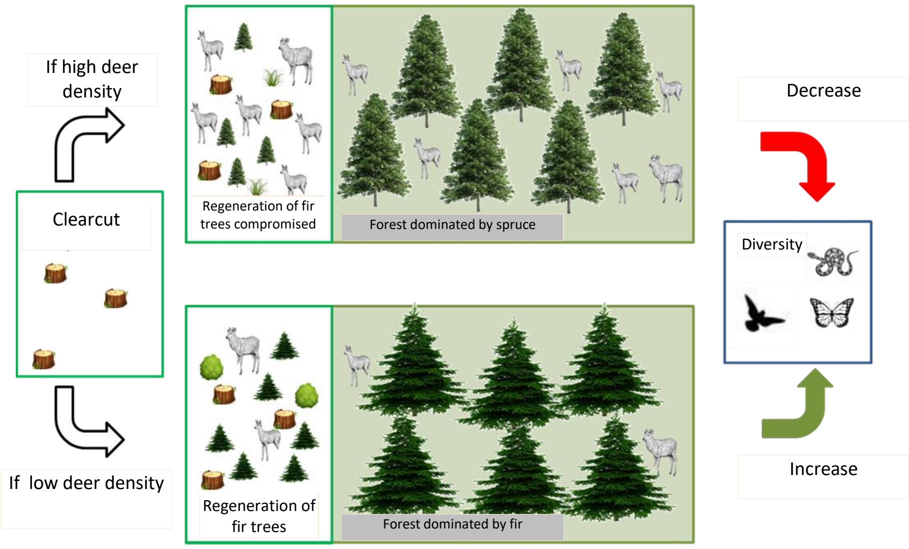


Figure 2-10: Successional trajectory following clearcutting of a fir plantation (ref. Bernard *et al.*2017; Chollet, 2012; Suding *et al.*, 2004)

2.3.5. Does post-clearcut treatment of slash (retention or removal, stumping, windrowing) influence biodiversity at stand scale?

Deadwood is a crucial support for biodiversity in forests. Large pieces of deadwood are particularly favourable, but twigs (diameter <7 cm) and stumps can also play a non-negligible role. Their gradual decomposition contributes to soil fertility. Post-felling treatment conditions can influence the availability of habitats (deadwood, soil) for biodiversity.

We assessed the reality of this influence by updating, through a bibliographic search in the Scopus database, the qualitative (Gosselin, 2004; Bouget *et al.*, 2012) or quantitative (Ranius *et al.*, 2018; Riffell *et al.*, 2011) reviews already available in the literature. The studies mainly concern slash harvesting (after log harvesting, and more rarely whole-tree harvesting) in boreal forests.

Despite the lack of long-term studies, a consensus emerges that **keeping slash** on the logged area has variable effects depending on the site and the species considered, but is generally positive for the richness of plants, saproxylic organisms, fungi and lichens, as well as for woody growth. For both flora and fauna, the retention of logging slash prevents the spread of invasive or generalist species, thereby helping to maintain specialist forest species. **Mechanised windrowing** of slash or stumps leads to impoverished plant communities with very different compositions, including more non-native or invasive species. Although not as favourable as keeping slash in place, it can modulate positively the negative effects of clearcutting on soil macrofauna. Windrows foster the abundance of small mammals and their predators. **Stump removal** has a greater negative impact than slash harvesting, particularly on communities of saproxylic organisms.

In the long term (>50 years) and on a landscape scale, simulations show that intensive harvesting of twigs and stumps could reduce the quantity and diversity of deadwood habitats and lead to extinctions of saproxylic species.

2.3.6 What impact does soil compaction have on biodiversity?

Over the past few decades, mechanised forest logging has become more widespread, with increasingly efficient but also increasingly heavy vehicles. The counterpart of this technical development is the compaction of forest soils and the creation of ruts, which are recent effects in the history of forestry management. With reference to the harmful effects on agricultural soils, it now seems crucial to address the **effects of soil compaction in forests**.

An in-depth literature review was carried out to summarise the effects of compaction induced by mechanised harvesting on forest stands, regeneration and biodiversity.

The main effects of soil compaction may be summarised as follows:

1) Negative effect on a large number of biological traits of trees, in particular **root growth** and **forest regeneration.**
2) In general, sharply reduced **microbial biomass** and associated enzymatic activity, as well as a modification of the **functional composition of microbial communities.**
3) High sensitivity of **ectomycorrhizal fungi.**
4) Less documented effects on **soil fauna**, but generally a negative impact on soil arthropod and earthworm communities.
5) Frequently positive effect on the species richness of **understory flora**, associated with a modification of taxonomic and functional composition, resulting in flora communities on compacted soils containing less forest-specialist, more ruderal, more heliophilic, more nutrient-demanding and more hygrophilic species, with more exotic or invasive species. In addition, long-term vegetation monitoring leads to the conclusion that soil disturbance by forestry machinery is an emerging cause of changes in the composition of understory flora in managed forests.
6) Little-documented effects of ruts on herpetofauna **(amphibians** and **reptiles**), but a negative impact on herpetofauna seems to have been established, as these artificial aquatic habitats act as population sinks.

Finally, research shows that **removing litter** (or baring the ground) has significant negative effects on the soil and biodiversity, and that these negative effects are often compounding those due to compaction.

To sum up, the damage caused to the soil by mechanised logging is substantial and long-lasting: it disrupts the functioning of the ecosystem, reduces forest productivity, makes regeneration difficult and adversely affects biodiversity. The specific recommendations in the Pratic'sols guide are designed to rationalise logging operation sites and minimise as much as possible the areas affected by compaction and rutting in French forests.

2.3.7 Can tree retention practices mitigate the impacts of clearcuts and other regeneration cuts on taxonomic biodiversity at stand scale?

In any type of felling, forest managers can maintain some habitat trees to preserve biodiversity, a practice known as retention. Can these practices mitigate the impacts of regeneration felling on biodiversity at stand scale?

We found enough studies for a meta-analysis to assess the overall effect of **retention** on local species richness, in the case of clearcutting retention, on the short term (in boreal and temperate forests). To assess the effects in greater detail according to **ecological groups of species**, **retention rate** and **spatial layout of retained trees** (isolated or in clumps), we compiled a narrative summary of previously published meta-analyses (Fedrowitz *et al*, 2014; Gustafsson *et al.*, 2010; Basile *et al.*, 2019; Rosevald and Lôhmus, 2008), documenting the case of clearcuts on the short term (<20 years), and encompassing cases without retention *stricto sensu*, such as temporary retention of seed trees.

Compared with clearcutting without retention and versus uncut controls, retention allows for hosting richer communities in the short and medium term, all taxa combined, at the stand scale. However, compared with the uncut controls, these communities are poorer in close-canopy forest specialist species, and richer in open-habitat species. In the long term (>50 years), stands resulting from clearcutting with retention are poorer in species than uncut controls.

The positive effect of retention increases with the proportion of trees retained (Fedrowitz *et al.*, 2014; Basile *et al.*, 2019). The effects tend to be more marked in the case of aggregate-tree retention. In order to reduce significantly the impact of clearcutting on biodiversity, at least 10 to 15% retention is required (or even much more, depending on the taxa).

Closed-canopy forest specialist species are more numerous in the uncut controls than in clearcut areas with retention or in simple clearcuts. On the contrary, open habitat species are respectively more numerous in the simple clearcut than in clearcuts with retention and in uncut controls.

2.3.8 What is the impact of ground preparation work on forest biodiversity?

After clearcutting, stands are usually regenerated by planting. Preparatory work prior to planting consists in treating logging residues (slash shredding or windrowing, sometimes stumping) and, more often than not, **mechanised work on the soil** (hooking (= scarification) or humus stripping to control competing vegetation, subsoiling or tillage to loosen soil compaction, ridging in case of temporary waterlogging). The benefits of mechanised site preparation (MSP) have been shown in France to limit planting failures. Effects of MSP have been identified on the physical properties of the soil and its biogeochemical functioning. However, by modifying the microclimate and the availability of organic matter, these effects are also likely to modify the soil's flora and biotic communities. A qualitative literature review was conducted to assess these effects.

A majority of studies compare plantations after clearcutting and MSP with a control planted without MSP on the same plot, in boreal or sub-boreal forests. Very few studies have been conducted in temperate or southern climates. The diversity of practices and contexts makes it difficult to compare the various studies cited.

As a general rule, although these effects vary according to pedoclimatic conditions and the type of ground preparation:

1) MSP modifies **floristic assemblages** by favouring certain groups (such as woody plants) and reduces species richness in the short term (Demarais *et al.*, 2017).
2) MSP leads to a general decrease in the abundance of the main **soil fauna** taxa (including microbes and fungi), some of which durably so (Marshall, 2000).
3) MSP also reduces the richness of **ectomychorizae** and modifies the composition of microbial and fungal communities (Marshall, 2000), in particular by changing the ratio between ectomycorrhizae and saprotrophs, which can disrupt the decay of organic matter in the short term.

2.3.9 What is the impact of a plantation on biodiversity, compared with natural regeneration of the same species?

Natural regeneration and plantation differ in terms of seedling/sapling density, level of soil disturbance, presence of secondary species and genetic diversity of the stand. These differences are likely to influence forest succession and biodiversity. What differences have been observed in biodiversity between naturally regenerated and planted stands?

A meta-analysis was used to assess the effects of the regeneration method **(planting** versus **natural regeneration**) on biodiversity, at an equal successional stage. In addition, we carried out a qualitative synthesis of nine literature reviews assessing the effect of various planting methods (pure or mixed, native or exotic species) against a forest antecedent (including Wang *et al.*, 2022; Albert *et al*., 2021; Castaño-Villa *et al*., 2019; López-Bedoya *et al*., 2021; Chaudhary *et al*., 2016).

Among the data collected for the meta-analysis, the usable data concerned only the short term (<20 years) and were too few in number for a quantified assessment. Conversely, summaries on the effect of plantations on biodiversity compared with the forest antecedent are relatively numerous and their findings are convergent: plantations generally lead to a reduction in biodiversity, or at least to changes in composition, particularly at the expense of native species. These negative effects may diminish over time, but not always. Choosing native rather than exotic species and mixed rather than pure plantations will help to mitigate the negative effects of planting, without however cancelling them out.

2.3.10 What is the impact of introducing an exotic species on biodiversity, compared with introducing a native species?

Faced with the risk of decline in forest species caused by climate change, the adaptation of existing species or the natural migration of species adapted to drier climates are generally considered to be too slow. Assisted migration or introduction of exotic tree species are among the solutions considered. These solutions could have an impact on forest biodiversity, as the identity of the main tree species in a stand is a determining factor of its biodiversity.

We present a qualitative summary of the literature on the relationship between the **residence time of a species** in an area and the **biodiversity associated** with it. Based on I2AF data[11] integrated into the *Inventaire national du patrimoine naturel* (INPN) and a literature review on the dates of introduction, we then classify the species inventoried by the IGN in mainland France into three categories: neophytes (species introduced during the modern era, i.e. since 1492), archaeophytes (species introduced before 1492) and autochthonous (naturally present on our territory without human intervention). Finally, we look at the risk of hybridisation between exotic and native species.

The biodiversity associated with a species increases with its residence time in the area, and therefore the potential coevolution with other species (Brändle *et al.*, 2008; Brändle and Brandl, 2001). Exotic species (especially neophytes) have a lower associated diversity, which is less specific (lower heritage value) than native species (Decocq *et al*., 2021). The introduction of an exotic species can lead to the introduction of other exotic species (including pathogens) that are linked to it, increasing the richness on a territorial scale. It can also alter the genetic diversity of genetically related native species. In a region with low afforestation rate, plantations can play the role of biological corridor, but to a lesser extent in the case of exotic species.

[11] *Inventaires archéozoologiques et archéobotaniques de France* (Archaeozoological and archaeobotanical inventories of France)

Part 3 | Historical, social, regulatory and economic analysis

Clearcutting is a forestry operation that has raised controversy for over two centuries. Currently much criticised by environmental associations, it is on the contrary regarded as relevant and necessary by foresters in even-aged high forests.

The issue of mass mobilisations against clearcutting is addressed in five questions covering (1) the establishment of a framework for analysing conflicts over clearcutting, (2) a historical perspective on conflicts since the 19th century, (3) an assessment of current modes and levels of public mobilization in France, (4) a comparative analysis of the arguments used by the protagonists in the debates, and (5) an exploration of the modes of resolution implemented on the ground.

The regulatory and economic aspects of clearcutting are addressed in four parts: (1) Regulatory knowledge of the French legal corpus, supplemented by a focus on the regulatory situation in other European countries, (2) Current status and foreseeable short-term development of certification processes, (3) Technical and economic analysis of the practice of clearcutting from the standpoint of reducing the size of cuts, and (4) Comparative economic analysis of treatments in even-aged (with clearcuts) and uneven-aged high forest, the evolution of the spatiotemporal structure towards uneven-aged forest being a possible path towards reducing the current use of clearcutting.

3.1 Past and present social mobilisations around clearcutting

3.1.1 How to study the conflicts and social movements about clearcutting?

A forestry conflict is characterised by a situation where groups of stakeholders (foresters, environmental non-governmental organisations, groups of citizens) operating in the same area express strong incompatibility of ideas, beliefs, behaviours, roles, interests or values concerning forestry methods, their impacts, or more generally the place and role of forests in the territories, and where the action of one of these groups prevents another from achieving their objectives. Depending on its configuration and outcome, a conflict can be a driver of social change (technical, economic, legal and/or political) or a form of resistance (Bulle and Tarragoni, 2021).

The conceptual and methodological tools of the sociology of conflicts and the construction of social problems show that conflicts are the result of **mobilisation** conducted by social movements. The institutionalisation of a simple 'disturbance' into a **social problem** goes through several stages (Neveu, 2015):

1) categorisation and denunciation of the problem by a group of stakeholders,
2) production of a rationale,
3) publicity and media coverage of the problem,
4) incorporation into a political agenda,
5) production of solutions negotiated between the conflict protagonists.

All of these construction phases to build up clearcutting into a social problem by some organisations (‘cause entrepreneurs’) are generally matched by counter-actions by opponents (interest groups) aimed at minimising the issue (Table 3-1).

Table 3-1: Strategies for constructing and deconstructing a social problem

“Cause Entrepreneurs”	**“Interest groups”**

1. Alert / denounce / dramatise	1. Ignore / refute / deflect
2. Objectivise / bundle together isolated cases / ramp up generalisation	2. Cast doubt on / produce a counter-diagnosis
3. Mobilise the public and the media	3. Mobilise peer networks / find an environmentalist backer
4. Win over public decision-makers to get the cause on the political agenda	4. Avoid putting the issue on the agenda / decide among peers and decision-makers
5. Propose / draft new standards	5. Re-legitimise existing standards / propose counter-solutions
6. Change practices and reference systems in the field / close the problem	6. Postpone decision-making / take symbolic measures

The **methodology** used to explore conflicts about clearcutting consists in studying symmetrically the protagonists' actions and arguments. To this purpose, we searched the literature for articles and scientific papers on mobilisations and conflicts over clearcutting (144 references, including 86 in France), online archives for the period 1850-1950, an inventory of online petitions (69 references), articles in the national and regional press (470 references) in 2021, and an analysis of speeches and writings available online on the websites of forestry and environmental organisations. By cross-referencing these various sources, we were able to produce an overview of past and current forestry conflicts and mobilisations in France about clearcutting.

3.1.2 What is the historical perspective of conflicts about clearcuts (19th century-2015) in France?

Conflicts over forest management have always existed. The first cases documented in the scientific literature of conflicts relating specifically to clearcutting date back to the 19th century. These social mobilisations were supported by the Barbizon painters in the Fontainebleau Forest in the **1830s to 1850s** (Fritsch, 1997; Kalaora, 1993), then by the Touring Club de France around 1910 (Deuffic & Banos, 2020; Schut & Delalandre, 2016). Complaints related to the **aesthetic and landscape impact** of these cuts. With privileged access to the political decision-making bodies, this artistic and bourgeois elite obtained from the public authorities of the time the creation of artistic series at Fontainebleau and the registration as natural monuments of a number of forest areas deemed emblematic, particularly in the Alps. A third period of protest emerged in the early **1970s**, around the Réno-Valdieu forest in the Perche region (Moriniaux, 1997), but also in Aisne, Aude and once again in Fontainebleau. Still led at the initiative of an intellectual elite, these mobilisations are now finding new allies in the first associations dedicated to environmental protection[12] as well as an internal trade union at the ONF[13]. The geographically scattered protest sites, the difficulty of shaping them into a national network and their very heterogeneous social roots mean that this third wave of environmental mobilisation is not really capable of decisively changing the direction of French forestry policy. Conversely, it introduces a new way of analysing the forest and its management methods in terms of environmental criteria. Backed by support from the political decision-makers in place, forestry institutions are not immediately responding to these environmental aspirations. Instead, they suggest mitigating the visual impact of clearcutting and conifer planting using landscaping management techniques (CTGREF, 1976). The proposals are designed to play on the shape of cutovers, position them based on the relief, create *trompe l'oeil* perspectives so as to reduce the depth effects of the cut areas (Breman *et al.*, 1992).

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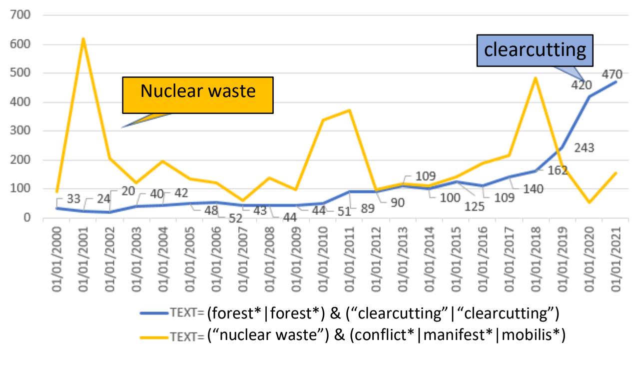
[12] *Nature et Progrès* created in 1964 or French branch of WWF created in 1973
[13] SNUPF: *Syndicat National Unifié des Personnels des Forêts* created in 1965, renamed *Syndicat National Unifié des Personnels des Forêts et de l'espace naturel* (SNUPFEN).

Emerging demands concerning the ecological consequences of various forestry models have not been fully taken into account when considering the landscape dimension. Yet in the **1990s** the development of ecological research increasingly raised questions about the **environmental impact of forestry methods**. In parallel, ecological protests against forestry production methods and clearcutting became chronic in some French regions such as Limousin and Morvan throughout the 1990s and 2000s (Moriniaux, 1996; Ruffier-Reynie, 1999). In an international context where sustainable forest management is being institutionalised, public forestry decision-makers can no longer ignore these environmental expectations. This is reflected in the recognition of the multifunctional role of forests in the law of 2001, the promulgation of a biodiversity strategy in 2004, the introduction of eco-labels (PEFC, FSC), etc. But this process of "greening" forestry policies is not linear. At the end of the 2000s, several reports highlighted the "*inadequate exploitation of French forests"* (Ballu, 2008) and argued that "*the time for harvesting has come"*. An increase in wood harvesting is presented as desirable from all points of view, and wood industry players are invited to "*change the scale of resource mobilisation"*. This "*productive turning point*" (Sergent, 2014) should be resituated in the context of the European Union's new energy policy, which aims to increase the share of renewable energy sources, particularly through the development of fuelwood. Everything is therefore contributing to ensure that a significant increase in the **mobilisation of woody resources** is placed on the political agenda, although without clearly explaining the issue of harvesting methods, and in particular clearcutting. In 2016, the national forest and wood programme (MAA, 2017) set a target of a 20% increase of the harvest. Yet 'mobilising resources' necessarily involves cutting wood. As early as 2010, some environmental organisations feared that this policy, that ignores environmental and social aspects, would lead to numerous conflicts (Neyroumande & Vallauri, 2011). Their intuitions have proven right, and while this call to harvest more wood is not the only cause of the current tensions, it does play a part.

3.1.3 What are the current levels and methods of mass mobilisation in France (2015-2021)?

Protests against clearcutting have been growing steadily since the 2010s. However, the **mobilisation methods**, their **media support**, the **profiles of players involved** and their numbers are changing significantly compared with the protests of the 1970s. The diversity, synergy and complementarity of mobilisation methods draw on a register that is both **traditional** (marches, site occupations, manual petitions, etc.) and **innovative** (digital petitions, web videos, web stories, national and European advocacy, etc.). Between 2016 and 2021, more than 60 digital petitions were published online to denounce clearcutting; some have received as many as 100,000 signatures. Similarly, while the national generalist press and the regional daily press published only 50 articles on clearcuts in 2010, over 470 were published in 2021 (Figure 3-1).



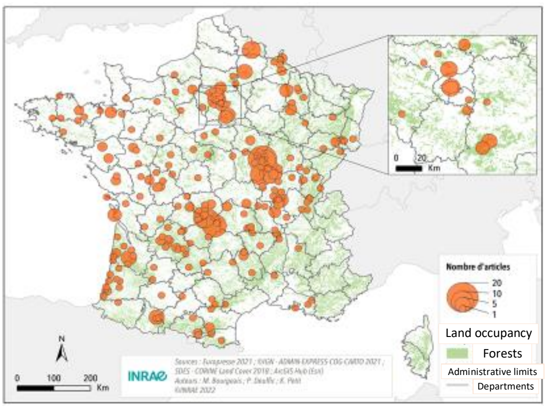


Figure 3-1: Media coverage of two types of environmental conflicts - clearcutting and nuclear waste - in the national and regional press between 2000 and 2021 (left) and location of mobilisations reported in the national and regional press in 2021 (right).

The current mobilisation phase concerns nearly all forests on the French territory, both public and private, with a concentration in the Île-de-France, Morvan and Limousin regions. These mass mobilisations are not just a media artefact, but reveal and publicize protests that have been simmering in certain areas for 20 years and have had difficulty making themselves heard beyond local circles. The coordination and professionalisation of activist groups, their use of a wide range of press and digital media, and their expertise in advocacy are giving new impetus to these movements.

These mobilisations reflect the **strong desire of environmental NGOs** and **citizens' groups** to influence debates on the role of the forest and its current management methods. Efforts to raise media coverage of clearcutting are intended to draw the attention of public authorities to the issue and pressure them to put it on the **political agenda**. They also aim to question the traditional interpretative frameworks of the industry ("*clearcutting is a normal practice*") and to propose counter-narratives ("*the principle and methods of clearcutting must be reviewed*"). To this purpose, they use the same strategies as professional forestry organisations, i.e. direct contact with the political and administrative spheres and regular pressure put on them. In fact, the growing number of protests and their media coverage are breaking the circle of traditional negotiations in select committees, and are modifying and restoring the balance of power between industry professionals and ENGOs. For example, participants in regional committees reviewing regional forestry management plans (SRGS) and eco-certification labels (PEFC and FSC) are discussing the introduction of maximum felling thresholds (2, 5 or 10 ha depending on the organisations and regional configurations).

3.1.4 What arguments are put forward? What factors explain these contrasting representations?

Conflicts over clearcutting are rooted in particular silvicultural and territorial situations, but are also closely linked to the current major forestry debates. For some social groups, clearcutting represents a technical and economic optimum, while for others it is a way of rejecting the industrialisation of forest management. The arguments for and against clearcutting generally fall into three categories (Table 3-2). From a **landscape** standpoint, the size and shape of clearcuts, their concentration in space and time, and the conditions under which they are operated are the elements most regularly criticised. Although woodland landscapes cannot be reduced to a fixed image, the continuity and discontinuity of woodland landscape dynamics attest to the ability of certain stakeholders to anticipate and give meaning to clearcutting, while others suffer these landscape changes, fuelling a feeling of powerlessness, resignation or anger. Similarly, the question of the surface area of clearcuts reflects the use of very different metrics. While advocates of clearcutting point to aggregated national indicators, which put the surface areas into perspective (67,000 ha/year of clearcutting and heavy felling, or 0.4%/year of the forest surface area), opponents object that the average accounting reality of these figures does not reflect the actual experience of the local inhabitants where the felling is carried out and its cumulative effects over short periods of time. From an **ecological** standpoint, the foresters justify clearcutting by invoking the notion of a landscape mosaic, which would be conducive to a diversity of environments and species. They also point out that the introduction of the FSC and PEFC eco-certification standards and various recommendation guides in the late 1990s led to changes in forestry practices by introducing rules to protect watercourses, prevent soil compaction and combat mechanical pollution. For opponents, the impacts of this practice on biodiversity, microclimate, soil microfauna and flora, erosion, water quality and soil compaction and fertility are still poorly assessed. The ENGOs would like a more precise impact assessment. Finally, from a **technical and economic** standpoint, advocates argue that clearcutting simplifies the management and development of stands and makes it easier to plan operations, whereas the introduction of area thresholds for clearcutting would reduce the profitability of management. For opponents, the criticisms focus on the negative externalities of clearcutting borne by the community, as well as on the economic development models of the regions induced by this type of forestry.

Table 3-2: Repertoires of arguments on clearcutting

"Bearers of grievances"	**"Interest groups"**
Landscape impact	
- Disappearance of mature trees - Size of clearcuts - Concentration in the territory	- Restricted definition of clearcutting - Minimising surface areas - Landscape integration techniques
Ecological impact	
- Biodiversity - Microclimate - Erosion/Water/Soil - Soil/above-ground carbon	- Creating a mosaic of environments - Precautions on felling sites - Carbon in building industry
Business model	
- Mechanisation: social progress? From musculoskeletal disorders to psychosocial risks (burden of bank loans)	- Technical/logistical simplification /cost optimisation /worker safety

Set against a backdrop of the '***ecologization***' and '***climatization***' of forestry issues (Aykut, 2020; Ginelli, 2017), these argumentative battles build bridges between problems. Consequently, clearcutting is a starting point that broadens the debate to include other issues such as the diversification of silvicultural practices and the assessment of their impacts, the role of forests in the energy transition, the relevance of carbon neutrality instruments, the plurality of forest governance methods, the effectiveness of eco-labels and ultimately rethinking the social contract between forest operators and users. These debates are therefore unlikely to be resolved on the strength of the best argument alone. While a rational confrontation of these various arguments remains essential to identify a common horizon, progress towards negotiated agreements will likely rely on arbitration between these differing registers of justifications.

3.1.5 What approaches are followed to resolve conflicts about clearcutting?

To deal with the conflicts about clearcutting, the protagonists resort to a combination of different types of solutions, none of which can resolve the conflicts on its own. While educating young people and mass communication with adults remain fairly traditional tools for raising awareness, they also have their limitations. In recent years, the use of broader-based participation and the establishment of **negotiating forums** at all territorial levels, and a plurality of organisations have emerged as a new way of restoring a dialogue between the stakeholders and of easing tensions. The success of these systems is conditioned by the way they are introduced and how the players use them. One of the pitfalls is to avoid turning them into mere rubber-stamping schemes for decisions already taken or taken elsewhere, or arenas where controversy is reignited and decision-making blocked. While discussions within schemes such as PEFC and FSC are leading to changes in reference standards, with the introduction of new thresholds, no binding regulations equivalent to those in other European countries have yet been promulgated. While the conflicts over clearcutting remain at the level of a binary opposition between the environment and the economy, **more precise questions** are emerging about the benefits and drawbacks of some alternative solutions with regard to climate change, biodiversity or landscape. These considerations are reflected in a shift - albeit difficult to assess today

- in **practices in the field**, less visible than a regulation recast, but having a non-negligible transformative impact, at least at local level. The critical re-examination of some silvicultural techniques has led forestry professionals to reduce on their own the size of cutover areas, diversify the reforestation species, etc. In a limited number of cases, they are even transforming their forests so clearcuts are no longer necessary to exploit the timber. These changes would undoubtedly have taken place at some point, under technical, economic, social or climatic constraints. The current protests against clearcutting are likely to accelerate this trend, while at the same time broadening the scope of issues to forest management and renewal methods, the contribution of forests to regional development, forest governance methods, etc. The conflictual or non-conflictual nature of these future debate topics will probably depend in part on how the discussion mechanisms are organised and on the willingness of the various protagonists to reach fair and equitable agreements for all concerned.

3.2 Regulatory aspects of clearcutting practices

3.2.1 What is the current situation in France regarding the regulatory framework for clearcutting in public and private forests, and what changes are envisaged?

The issue of **regulatory control on clearcutting** is currently particularly acute in France. One of the debating points is the benefit of thresholds beyond which clearcutting could or should be banned. The goal of this work was to identify and analyse what, in the Forestry Code and the corpus of regulations as a whole, relates to the following questions:

- Is clearcutting defined and governed by legislation or regulations?
- Is there a legally set threshold above which clearcutting is prohibited?
- If there is a threshold, is it set by national, regional or departmental legislation?

Our analysis was based on an extensive literature review, and on consultation and analysis of the legislative and regulatory texts of the Forestry, Environment, Town Planning and Rural Codes.

There is no national-scale definition or regulatory framework for clearcutting, whether in private forests or in forests governed by the national forestry regime. In forests covered by a **Sustainable Management Document** (DGD, *Document de Gestion Durable*), guarantees are provided by the approval from public authorities. The only **regulatory obligation** following clearcutting addresses **reforestation** (art. L. 124-6). This provision requires foresters to reforest within 5 years post clearcutting or logging of an area exceeding a threshold set by the Prefect of the Department. With the exception of this reforestation obligation, the Forestry Code does not distinguish between clearcutting and other types of felling. At departmental level, a threshold may be set by the Prefect for felling that removes more than 50% of the volume of high stand (art. L. 124-5 – Figure 3-2). This system excludes coppicing cuts.

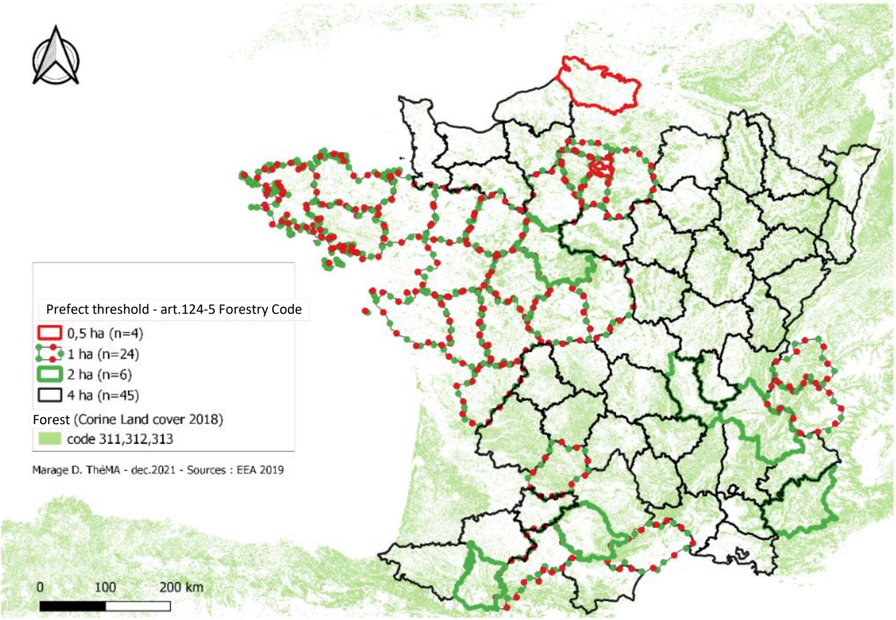


Figure 3-2: Breakdown by Department of the Prefectoral thresholds for authorisation of felling that removes over 50% of the forest volume under article L. 124-5 of the Forestry Code

3.2.2 What is the current status and foreseeable short-term development of certification processes?

French forests can be covered by two certification schemes, PEFC and FSC. These two forest management certification systems include two **specifications** that address clearcutting via a number of criteria. Revisions of the respective requirements have been underway since 2021 and will be completed in 2023.

Until now, the PEFC requirements on clearcutting have focused on the size of these types of cuts, limiting them to between 2 and 5 hectares on 30% or steeper slopes, and between 10 and 25 hectares in other cases, except in special documented cases. There was no PEFC definition of clearcutting. FSC's current requirements on clearcutting provide a definition and limit its size to 2 hectares on slopes (>40%) and 10 ha in other cases, except in the Landes department (25 ha).

Discussions on the revision of these two reference systems tend to propose definitions on the one hand, and on the other hand, **reductions in the size of eligible areas**, or even **prohibitions** in some cases of special habitats. For PEFC, a definition is proposed as well as bans in the forest areas of high ecological value as defined by the decree 2022 527 of April 12th, 2022 and in the riverbanks; the size is reduced to 2 ha on slopes, a target is set at 5 ha and any other clearcutting of up to 10 ha must be justified, except in the case of single-species plantations. For FSC, the trend is the same, with bans for certain habitats or conservation networks, and size limits that have not yet been set but are smaller than the current references.

3.2.3 What is the regulatory framework for clearcutting in different European countries?

The practice of clearcutting is regulated in most European countries, but the institutional and legal arrangements vary widely from one country to another. The analysis of clearcutting regulations must be considered in the context of national forestry policies and the role of forests in the economy and life of these regions.

The following questions were assessed based on a literature review of regulations in 23 European countries:

- Does the regulation take into account the characteristics of the cuts (size, shape, volume, etc.)?
- Are the determining factors of such limitations of an ecological, landscape, economic or societal nature?
- Are these differences explained by differences in legal systems? Is a consistent vision emerging at European level?

Certain limitations exist in some countries depending on their forestry history and biogeographical contexts. A major forestry country like Finland does not dictate any limits on clearcutting. The same applies to the UK, Spain and France. Conversely, five countries where forests are mainly located in mountainous areas, namely Switzerland, Slovenia, Slovakia, Italy and Bulgaria, totally ban clearcutting (Figure 3-3). Exemptions are however possible and these bans exclude coppice cutting. Other countries restrict clearcutting based on thresholds that vary according to administrative regions, as in Germany (Figure 3-4), to stand type, as in Romania, to soil type, as in the Czech Republic and the German Saarland, or the nature of the ownership, as in Poland and Lithuania.

Since around 1970, several countries have tightened their legislation and laws governing clearcut areas and permit granting (Onida, 2020). These include Belgium, Hungary and the Czech Republic. In connection with the implementation of the principles and criteria for sustainable forest management and certification, the criteria for determining where clearcutting is permitted, as well as its size and shape, are currently under review in several countries (Ireland, Spain, Sweden, Norway), due to the importance afforded by society and environmental NGOs to its effects on the landscape and the functioning of ecosystems. So far, no consistent vision has emerged, probably due to the lack of a European forestry policy (Wolfslehner *et al.*, 2020; Sotirov *et al.*, 2022).

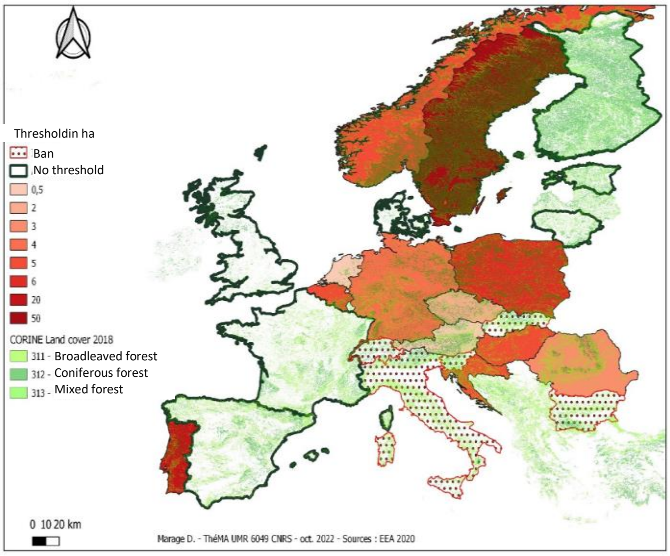


Figure 3-3: Maximum regulatory threshold for clearcutting in European countries

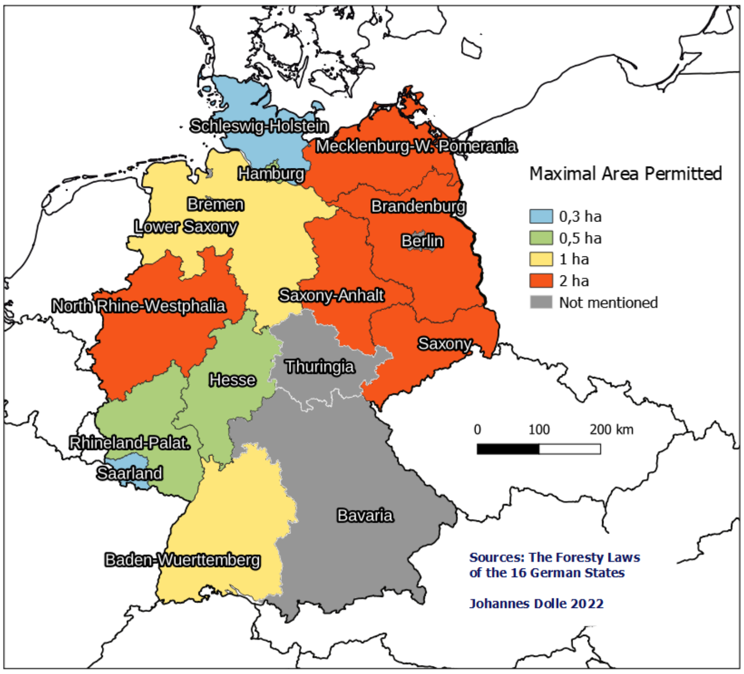


Figure 3-4: Regulatory threshold for clearcutting in the 16 German Landers (ref. Dolle, 2022)

3.3 Technical and economic analysis of clearcutting practices

3.3.1 What are the general technical and economic characteristics of clearcuts?

Clearcutting is a response to diverse issues that vary over time. While it seems normal to consider these issues, it must be acknowledged that they are rarely expressed, and clearcutting is most frequently studied from the standpoint of limitations (particularly ecological and landscape) than benefits. A summary literature review was therefore carried out in this assessment.

With the exception of coppicing cuts and land clearing (change of land use), which are special cases, clearcutting is associated with the subsequent plantations. In some cases, they result from a disaster or a failure of natural regeneration. When clearcuts are intentional, they are sometimes related to **ecological reasons** (species behaviour, adaptation to local conditions and to climate change) or **ergonomic reasons** (lower risk of accidents, easier mechanisation). But the predominant rationale is often **economic** (seeking to increase stand productivity, adapting to the timber market, reducing some costs by concentrating operations in space and time, avoiding injury to standing trees, etc.). The rationale is also largely **logistical** (streamlining of operations, renewal, protection, management, monitoring, etc.).

The research prospects consist in assessing the economic consequences of constraints on clear-felling in order to compare them with their ecological and landscape effects, and find a balance between economics, ecology and societal expectations. The goal is to keep working on both questions to find answers as outlined below:

- What are the economic implications of reducing the size of clearcuts?
- What are the economic benefits of converting from even-aged to uneven-aged high forest?

Some bibliographical references: Beck *et al.* (2021), Kimmins (1997), Sotirov *et al.* (2022).

3.3.2 What are the economic implications of reducing the size of clearcuts?

Beyond the opposition between clearcutting and continuous cover systems, there is a whole range of situations depending on the surface area of the open canopy areas, from gaps of a few ares to complete plots of several dozen hectares. If the ecological and landscape impacts of clear-felling increase with its extent, what about the costs associated with harvesting and reforestation?

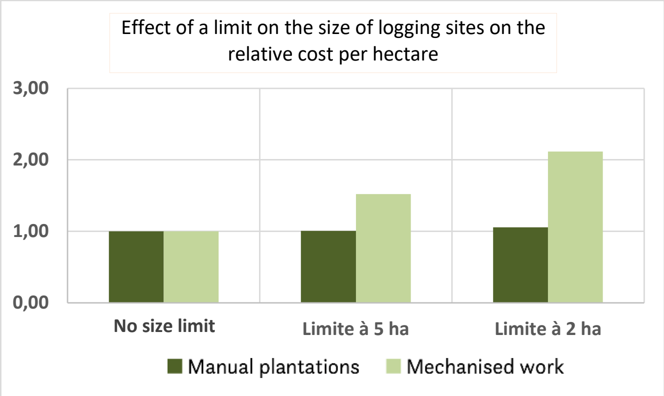
The cost of a project breaks down into fixed costs that are independent of the size of the project (administrative and technical management, logistics) and variable costs that depend on the scale of the activity (wages, consumables, equipment wear-and-tear, etc.). On a per area-unit basis, variable costs remain unchanged as the size of the site increases, while fixed costs, and therefore the cost of the harvesting site decrease proportionately. The cost per hectare was analysed for nearly **20,000 elementary logging sites** under the oversight of either the **ONF** between 2017 and 2020, or **Alliance Forêt Bois** (AFB) between 2020 and 2022.

The sites monitored by AFB are on average larger than those monitored by ONF (6.5 ha versus 3.3 ha). They are also more mechanised, which means that average costs per hectare fall more sharply with the size of the worksite. The number of logging sites would be approximately doubled with the felling area limited to 5 ha for AFB and 2 ha for ONF. In the absence of compensatory measures to coordinate the various logging sites in order to avoid their proliferation, the cost per hectare of mechanised work would increase by 50% if the size of the logging sites were limited to 5 ha, and would double if they were limited to 2 ha. As far as manual plantations are concerned, the consequences would however appear to be minor. In cases where the increase in the cost per hectare is high, it is likely to impact both the forestry contractors and the profitability of silviculture, and more generally the creation of value. While it is impossible to quantify all phenomena involved, we can expect a certain decline in timber harvesting, less reliance on mechanisation but greater use of imports or materials other than wood, and consequently, an increase in carbon dioxide emissions (due to imports and the growing number of logging sites).

The research prospects involve better assessing the consequences of clearcutting limitations:

- At microeconomic level, by broadening the range of operators taken into account, particularly in the private forestry sector.
- At macroeconomic level, by better quantifying the potential above-mentioned consequences on timber harvesting, imports, mechanisation and carbon dioxide emissions, among others.

Figure 3.5: Multiplying factor of cost-per-hectare increase at logging sites when their size is limited to 5 ha or 2 ha based on ONF and AFB data.



3.3.3 What is the economic opportunity of converting from even-aged to uneven-aged high forest?

Continuous cover forestry (CCF) systems, including uneven-aged high forest, make it possible to avoid clear-felling provided they are compatible with the natural environment and existing forest stands.

When the goal is to limit the effect of clear-felling, it is therefore useful to analyse whether or not it is advisable, depending on the cases and perspectives, to convert an **even-aged high forest** into an **uneven-aged high forest**.

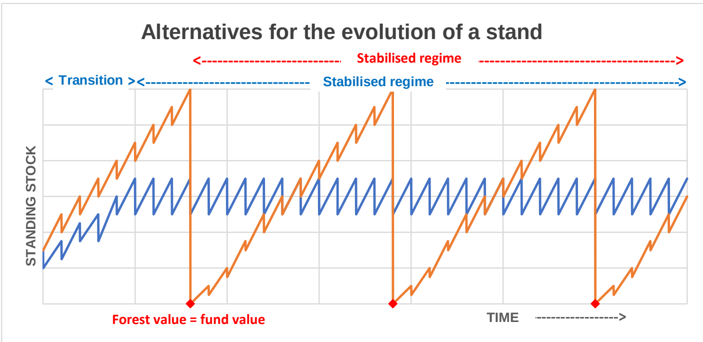
Such a comparison can be made using the economic methods for natural resources (especially to address timber supply) and the environment (taking into account all other ecosystem services, most of which are non-merchantable). The only accurate method consists in estimating, for different management options, the value of a given forest from the sum of all the future net benefits expected from it; the method then suggests selecting the option that allocates the highest value to the existing forest. The options usually converge towards a stabilised regular or irregular structure, preceded by a period of conversion between the current and future system. As comprehensive optimisation can be unwieldy, the methods used are usually approximate, which requires putting into perspective the analysis of the lessons to be learned.

The literature review shows that the findings do not support either system, and are highly dependent on assumptions and parameters. Among the trends that emerge, however, it may be noted that young or older even-aged stands are not suitable for immediate conversion, that the constraints imposed on management have a cost that can change the results, that a strong preference currently favours conversion to uneven-aged high forest, and that the risks may weigh more heavily than the choice of a silvicultural system.

The main areas of research focus essentially on the conditions for applying existing methods in France:

- There is a lack of data on all ecosystem services.
- There are very few growth models for uneven-aged high forest, and even fewer for any forest regardless of its structure (which would make it possible to analyse conversion between systems).
- The multifunctionality of forests is often considered in an expeditious manner, and considerable developments are needed to gain a more realistic vision.

Figure 3.6: Example of evolution of the forest growing stock based on two options: transition to even-aged (in red) or uneven-aged high forest (in blue). In both cases, a transition precedes a stabilised regime. In the case of even-aged high forest, the stock returns to zero at the end of a cycle and at the start of the next.



Selected bibliographical reference: Knoke (2012).

Part 4 | Analysis of renewal methods in the context of climate change

The renewal of forests ensures their long-term survival and, by extension, the retention of all the ecosystem services they provide. Renewal can take place (i) by natural regeneration, the most frequent method in France, particularly in broadleaved and mountain forests, (ii) by vegetative propagation (coppice shoots), mainly used in broadleaved stands in the southern part of the country, (iii) by planting, mainly for coniferous forests, and (iv) by seed sowing, currently a very uncommon practice in France.

Against a backdrop of climate change, increasing biotic hazards and evolving societal demands, the objectives and conditions of forest renewal are changing. To ensure the latter, the challenge is to adapt management practices and shift towards an optimised organisation of the sector, in order to establish young stands capable of adapting to future conditions that will be both limiting and uncertain.

The following topics are addressed successively: (1) Supply of forest seeds and seedlings, (2) Success factors for forest renewal, (3) Influence of renewal practices on biotic damage, and (4) Improvement of renewal practices in the context of climate change.

4.1 Supply of forest seeds and seedlings

4.1.1 What is the trend in sales of forestry seedlings and areas planted in France from 1992 to 2020?

Plantations have contributed to renew forests since the 17th century in France. An inventory of plantations between 1992 and 2020 was conducted based on surveys on seedling sales, IGN forest inventory data and bibliographical sources.

Historically, forest plantations had very different purposes, depending on the era: timber supply for Navy ships, construction lumber production, development of uncultivated land, restoration of mountain forests or damaged forests, and more recently adaptation to global changes.

Over the last 20 years, an average of 60 million seedlings have been sold (and mostly planted in France) every year. The quantity and type of seedlings sold are sharply influenced by public policy and by restocking activities following natural disasters (storms, dieback). The end of planting subsidies via the National Forestry Fund (FFN) in 2000 led to a drop in seedlings sales, with the notable exception of maritime pine, mostly planted in the Landes de Gascogne region.

According to the IFN, the average annual **plantation area** has fallen sharply since the start of the FFN (National Forest Fund, 70,000 ha/year in 1949), reaching a low of 30,000 ha/year in the 2000s and rising again to around 50,000 ha/year in 2015-2020.

Historically, plantations have focused on conifers, but recent changes in the objectives of plantations (diversification and adaptation) are encouraging broadleave plantations. Since the 2000s, the forestry seedlings market involves essentially three species: maritime pine, Douglas fir and sessile oak (versus six major species in 1992, the same species plus Norway spruce, beech and Corsican pine). At present, certain species suffering severe dieback are in decline (ash, Norway spruce, Norway spruce, silver fir, beech), while other species are emerging (Atlas cedar, Turkish pine *Pinus Brutia*, Salzmann pine, Turkish fir, Greek fir, downy oak), particularly in connection with the adaptation of forests to climate change (Table 4-1).

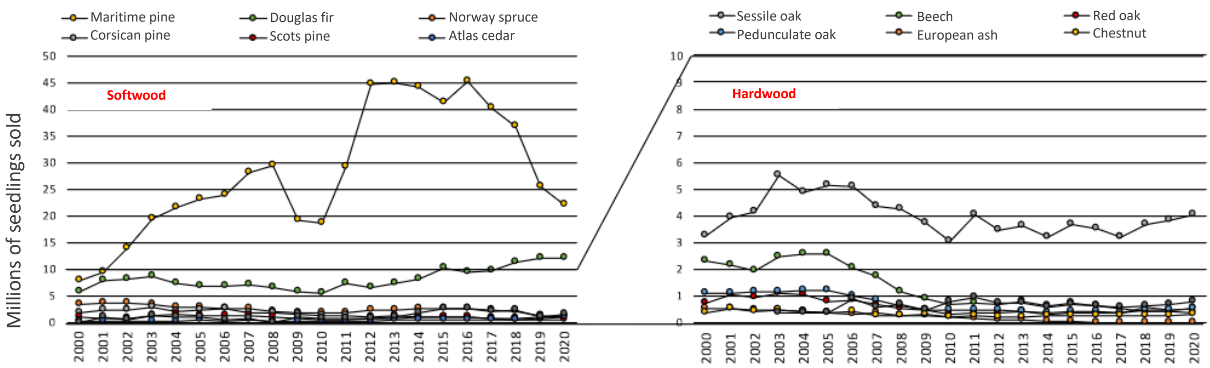


Figure 4-1: Number of seedlings sold annually in France, for the main softwood and hardwood species from 2000 to 2020

Overall, the plantations carried out since the post-war era have not drastically transformed the nature of the forest in mainland France; in 2017, around 13% of the forest area had a plantation forest appearance, according to IFN surveys.

Table 4-1: Sales trends since the 2020-2021 season

	Species	Reason(s) identified
Extinction ✕	European ash	Chalara ash dieback
Very sharp drop ↘↘	Norway spruce	Bark beetles
Decrease ↘	Silver fir Beech	Dieback
Stable →	European larch and hybrids Scots pine, loblolly pine, Aleppo pine, stone pine, Austrian black pine Sycamore maple, chestnut, pedunculate oak	-
Increase	Douglas fir	Forest renewal needs Economic interest
	Corsican and Calabrian pine	Cyclical
	Maritime pine	Impact of 2022 fires Economic interest
	Holm oak, cork oak, Turkey oak	Diversification
	Sessile oak	“a safe bet”
	Red oak	Cyclical
	Norway maple, wild service tree, sorb tree, wild cherry, linden/lime tree	Diversification, climate change
Very sharp increase ↗↗	Atlas cedar Brutia pine, Salzmann pine Turkish fir, Greek fir Downy oak	Adaptation to climate change (but still very small areas)

4.1.2 What are the obstacles to supplying the sector with reproductive material expected for future plantations?

In France, the need for **forest reproductive material** (FRM) will increase sharply, particularly as climate change leads to forest dieback and sustained effort on forest renewal, resulting in high demand, particularly for certain species. Public authorities are supporting these transformations (France Relance plan, France 2030 investment plan). Achieving the ambitious forest restoration targets is dependent on a steady supply of high-performance, diversified FRM. To this purpose, it is necessary to have sufficient **seed resources** (selected stands, seed orchards) adapted to the new needs, and a production capacity (seeds, seedlings) capable of meeting the growing demand.

France has a well-structured and organised FRM sector at national scale. Few data to measure the volume of forest seeds and seedlings volumes integrated into the industry, and few indicators are however available to forecast their development in the near future. Assessment of the trends in upcoming changes regarding the choice of species and provenances are currently based on the expertise of industry players.

In recent years, some cyclical or underlying shortages of FRM have been observed. Causes were multi-factorial: phytosanitary and/or climatic issues affecting flowering; natural hazards for fruiting; but also failures by the industry to anticipate its needs (species, provenances).

The number of **seed orchards** is currently being gradually renewed. This impetus needs to be complemented by work on plant variety breeding, in order to keep benefiting from research findings. Production facilities (seeds and seedlings) are calibrated to meet growing demand. They do, however, need to be modernised to meet the new requirements of quality, diversity and speed of delivery for FRM.

It is vital to anticipate forest managers' needs as much as possible, in order to produce the seedlings they expect, while taking into account the time needed to harvest the seeds and manage the crops. Otherwise, some FRM will never be available.

4.2 Success factors for forest renewal

4.2.1 Obtaining natural regeneration: How satisfied are forest managers?

Difficulties in establishing **natural regenerations** are currently becoming more frequent and more intense throughout the world. In France, recent studies carried out in a number of major forest contexts regarded as problematic (mountain fir/spruce/beech stands, lowland hydromorphic oak grove, pine groves of the Aquitaine dune forest, Mediterranean oak grove) have shown low levels of natural regeneration, which do not ensure satisfactory stem recruitment. However, the available studies do not provide any overall picture of the state of forest regeneration.

A **survey** was conducted in October 2021 as part of the CRREF assessment (372 responses received) to estimate the level of satisfaction of forest managers with the natural regeneration they have carried out in various forest contexts.

Three different criteria were proposed. The **woody composition and diversity** criterion received 58% positive responses ("Very satisfied" or "Satisfied"), the **stem density** criterion 71% and the **canopy cover and forest microclimate** criterion 76%. Overall, 45% of responses were positive for all three criteria simultaneously and 13% were not positive for any of them.

In the case of even-aged beech/oak high forest in the North-East, and even- or uneven-aged beech/conifer stands in mountains, around two-thirds of forest managers are satisfied with the regeneration obtained. The remaining third consider that they are not satisfied. In the even-aged beech/oak high forest in the Centre and North, the level of satisfaction is generally higher.

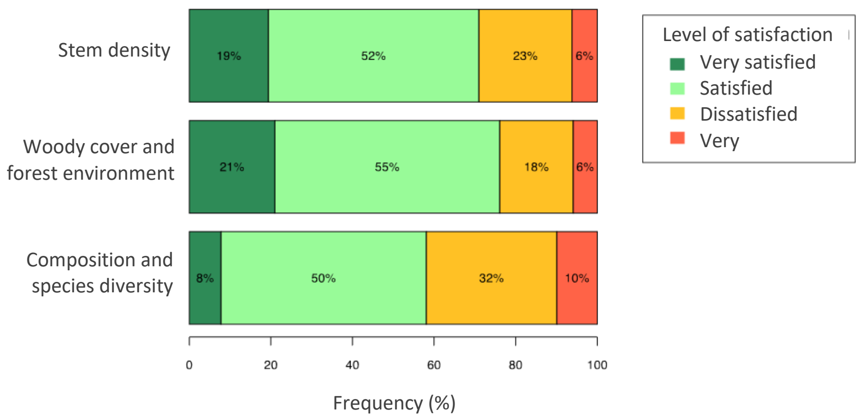


Figure 4-2: Satisfaction with natural regeneration according to three criteria, expressed as a percentage of the number of responses in a survey conducted in October 2021 in France (n = 372)

4.2.2 What are the expected effects of climate change on natural regeneration?

In recent decades, climate change has created weather conditions that are less favourable to the natural regeneration of forests. An literature review was carried out on this subject.

The regeneration process is divided into successive stages, which respond in different ways to climate change. **Fertility** (which combines the flowering, pollination and fruiting phases) responds to climate change in very different ways depending on the species. On average, it is however highly dependent on temperature and is generally favoured by higher temperatures than those currently prevailing. Conversely, **recruitment** (which combines germination, establishment and seedling development phases) will be adversely affected by higher temperatures and lower water balances, compared with current conditions.

In temperate lowland forests, the **competitive effects** of vegetation and adult canopy on seedlings are generally more marked than the **sheltering effects**, and the retention of vegetation or adult canopy above the seeds and seedlings is generally unfavourable to their development. In the future, if climatic conditions become drier, the shelter provided by the plant cover will become more important and could outweigh the negative effects of competition.

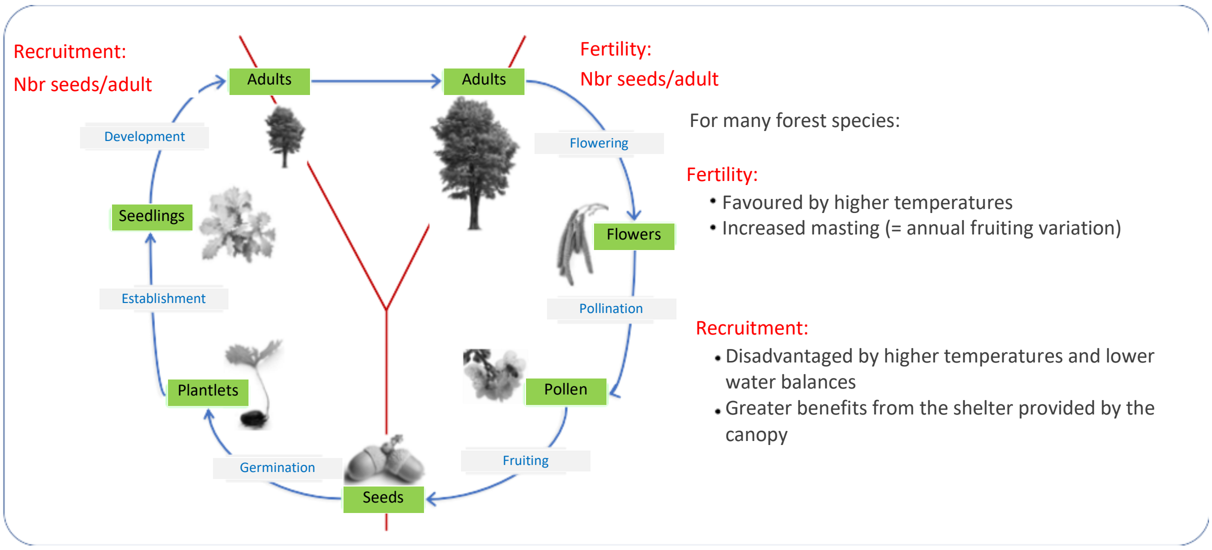


Figure 4-3: Breakdown of the regeneration process and impact of climate change on the various phases

4.2.3 How has the success rate of first-year plantations changed over the last few decades?

The first plantation year is a crucial period for **successful planting**, because of the vulnerability of the seedlings leaving the nursery, transport, storage and the climatic and biotic constraints that affect their establishment in the field.

Since 2007, the Department of Forest Health (DSF, Ministry of Agriculture) has been conducting a nationwide **survey** of plantation success. Every year, around 1,000 plantations are investigated at the end of the first year. The sampling reflects the diversity of species planted in the various regions. The survival rate is counted, and the causes of mortality are determined as far as possible, whether biotic (insects, fungi, large mammals, rodents), abiotic (drought, frost, etc.) or anthropogenic (quality of seedlings, planting work). A plantation is considered successful if more than 80% of the seedlings are living.

Over the 14 years of monitoring, 12% of the seedlings died and 18% of the plantations were unsuccessful. There is considerable variability between years: 2015, 2018, 2019 and 2020 (years with a high summer water deficit) showed between 25% and 30% of unsuccessful plantings. Conversely, in 2013, 2014 or 2021 (rainy years), only 10% of plantations failed. **Climatic conditions** are the main factor of success: 85% of seedling deaths are attributed to an abiotic (usually climatic), complex (interaction of several factors) or undetermined cause, 8% to attacks by large mammals or rodents, 5% to insects and 1% to pathogens. The impact of pathogens is most likely underestimated due to diagnostic difficulties.

Poplar and maritime pine have the best survival rates. These **species** benefit from optimised silvicultural practices, from sites less impacted by climate hazards (poplar) and greater tolerance to water deficit (maritime pine).

There are major **regional disparities**: the Corsica, Mediterranean, Grand-Est and Centre-Nord regions have lower than average regrowth rates, which can be explained mainly by the unfavourable weather conditions in recent years (Tallieu *et al.*, 2022).

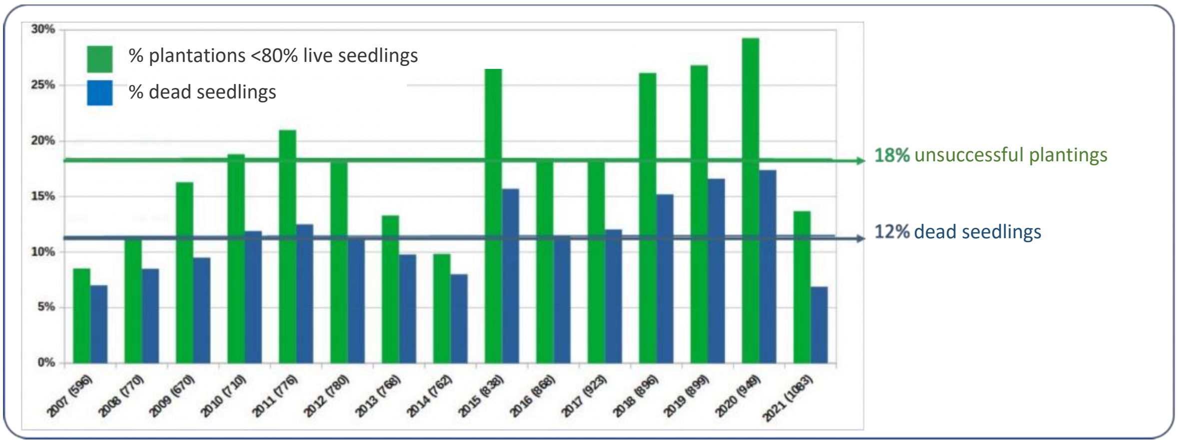


Figure 4-4: Percentage of dead seedlings and percentage of unsuccessful plantations per year, from 2007 to 2021, all species combined (DSF national survey)

4.2.4 How can transplant stress be mitigated to ensure plant establishment in the context of climate change?

The transplantation chain of a seedling, from the nursery to the planting site in the forest, is a critical process for successful reforestation. A young tree is effectively established when it has set up a functional root system to acquire the water and nutrients the seedling needs to survive and grow. Any dysfunction in the root system and any alteration in the circulation of water between the soil and the plant generates stress for the seedling. Meteorological accidents (drought, early heat and late frost) exacerbate the constraints on seedling survival and growth. The literature review highlighted two levers for action: one on seedlings and the other on the planting environment.

Differences between juvenile behaviour and climatic niche mean that species should be chosen according to their future potential, but also according to the robustness of the seedlings to meteorological incidents. The **biological characteristics of the seedlings** determine their ability to overcome water stress during transplanting, particularly their root growth potential. Under conditions of high water stress, seedlings with larger collar diameters are more resistant to stress. Containerized seedlings with large containers seems to give better results. Rapid transport of seedlings during the dormant period and careful storage before planting also guarantee quality and successful establishment.

Mechanical site preparation reduces the risk of transplanting stress, mainly by reducing competing vegetation in the immediate vicinity of the seedlings. Conversely, during heatwaves, a vegetation canopy may protect seedlings, and its retention may be beneficial. In arid zones, water management techniques can limit the intensity and duration of water stress during droughts.

4.3 Impact of various biotic stressors on renewal and influence of practices on biotic damage

4.3.1 How can the main pathogens and pests threatening forest stand renewal be monitored and their impact mitigated?

Pathogenic fungi and **insect pests** cause damage (mortality, stunted growth, deformation) in forest renewal stands. Identifying, quantifying and gaining a better understanding of pests is essential in order to assess the impact of pests, particularly exotic pests in forests, and to design pest control methods. This summary is based on records of damage caused by pests taken by the DSF's correspondent-observers as part of the **health monitoring** carried out on plantations and natural regenerations (5,000 reports per year), and on the **annual plantation survey** (12,000 plantations) over the period 2007-2021.

Nearly 400 pest organisms (fungi or insects) were noted. However, only around fifteen or so pests really pose a problem. Some can be lethal, such as *Hylobius abietis* on conifers, oak powdery mildew, Chalara ash dieback, and Armillaria root rot on conifers. Others, such as Sphaeropsis tip blight, Dothistroma (red band) needle blight and the pine processionary caterpillar, can cause deformations, stunted growth or shoot mortality. A significant proportion (25%) of the pests implicated have exotic origins. There are major spatial disparities among pests due to the host’s limited range (parasites specific to maritime pine or poplar), climatic requirements (Douglas fir Swiss needle cast, forest cockchafer), or an ongoing invasive process (Douglas fir needle midge).

The pine weevil (80% of entomological or pathological deaths) was the subject of a specific assessment. Various vulnerability factors have been identified, linked to the tree species (Douglas fir, Sitka spruce and Norway spruce are the most attacked species), the species in the previous stand (Douglas fir, Sitka spruce and Norway spruce are the most attacked), the time between felling and planting (attacks diminish progressively and are low after a period of 3 years), or the site preparation (slash piles foster attacks, soil scarification reduces them).

Global changes suggest that biotic problems can be expected to amplify. As curative pest control is limited in the forest, preventive control measures (silvicultural operations, monitoring, diagnosis) provide the most important levers.

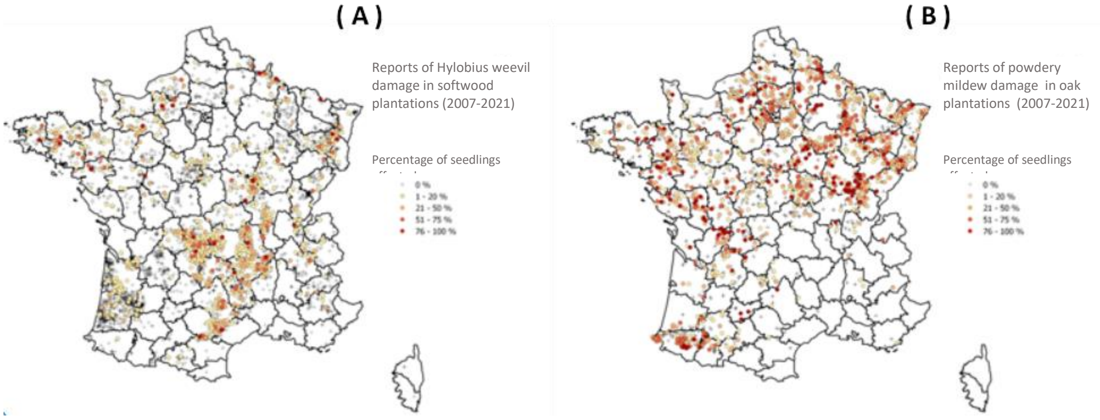


Figure 4-5: Reported damage caused by the two most common pests: A) Hylobius weevil and B) powdery mildew, from 2007 to 2021

Selected bibliographical reference: Saintonge *et al.* (2023a).

4.3.2 How can the impact of large ungulates be prevented and mitigated to enable the renewal of forest stands?

Populations of **wild ungulates** in France have been growing steadily for several decades. Young trees are vulnerable to browsing and the damage inflicted can severely impair their renewal. The level of palatability of the various species, combined with their resistance and resilience to browsing, grants them competitive benefits or drawbacks. In the presence of ungulates, species that are less browsed and/or more resilient to browsing will be advantaged over more browsed and less resilient species (Côté, 2004).

A summary was produced based on expert opinions, bibliographic databases, and findings from routine monitoring.

Restoring the forest/game balance by **reducing populations** is the measure that will have the most pronounced, overall and direct effects on the quantitative and qualitative improvement of stand renewal (Redick and Jacobs, 2020).

The use of **protective or repellent devices** is a stopgap solution that temporarily avoids the damage, but with monetary, social and environmental costs that should be closely assessed.

The various techniques for managing understorey vegetation have a secondary effect on damage reduction. At moderate population levels, this work proves fruitful and the role of ungulates can also prove beneficial for regeneration (Stokely and Betts, 2020).

Finally, the damage caused by ungulates to stand renewal is a major obstacle to implement strategies of climate change adaptation in managed forests, both to ensure successful new species plantations and to acquire a structural complexity designed to increase the resilience of the stands. (Champagne *et al.*, 2021)

4.3.3 How do the forest stand renewal method and the management sequencing influence damage by small rodents? What methods can be recommended to mitigate them?

Within the forest ecosystem, small rodents contribute to the dissemination of seeds and surface tillage, and are preyed upon by predators. The **damage** they cause in young **forest plantations** mainly occurs in the very early stages. The main medium-altitude mountain ranges in France (Massif Central, Vosges, Jura) are particularly affected. The damage reported by DSF (Department of Forest Health) originate from the health monitoring program and annual surveys on plantations success. The international literature addresses mainly microrodent population dynamics, with little data on damages and control methods (Jacob and Tkadlec, 2010).

During the demographic development of small rodents in grasslands, predators move from forest to grassland environments, making it easier for damage to occur in forests. Microrodents are very sensitive to the introduction of forest seedlings from nurseries, which are frequently spotted and browsed in the days or weeks following their establishment. The damage caused by these rodents affects the roots and the crown (field and water voles), which are barked or even cut off, and the aerial parts above the crown, which are most often barked (bank vole). The damage is essentially linked to the rodent species implicated, affects hardwoods more than conifers, and occurs mainly in the first part of winter. The larger and the more continuous the stand, without any perching trees for raptors, the more difficult it is for predators to hunt. Although damage has been low overall since the early 2000s, in 30% of reports on rodent damage, all or part of the plantation is jeopardized.

Since rodenticides should not be used due to the risk of poisoning non-target wildlife, prevention is the only feasible option. If operators observe rodents (sometimes easily) during early autumn planting, it is then preferable to stop the planting work and postpone it until late winter, when the population level will have dropped.

In the future, climate change will lead to a lengthening of the plant growing season and the rodent breeding season, which should result in a population increase. The risk of damage from small rodents is therefore likely to increase, especially if planting is favoured as a method of forest renewal.

4.4 Improving renewal protocols in the context of climate change

4.4.1 How to choose rationally the density and planting pattern of monoculture stands?

When planting is the chosen option for forest renewal, three questions arise: (i) What are the current and future production capacities of the stand; (ii) What species will be able to develop there with minimum risks in the medium and, if possible, long term; (iii) How should the chosen species be planted? Regarding the latter question, the **choice of density** and **planting pattern** needs to be carefully considered, as they have major impacts on the future growth dynamics of the stand.

Riou-Nivert (2019) has drawn up an inventory of the factors influencing the choice of planting density, grouped into four categories: technical, environmental, economic and sociological. On this subject, already well documented in the scientific literature, a literature review was conducted with a special focus on the impact of layouts. See also West (2013).

Planting density affects tree growth rate, crown development, wood quality and total stand production, and is therefore directly linked to the objectives of the silvicultural treatment. For some species traditionally planted in France, IGN (2017) has shown that the densities used have decreased overall in recent decades. For the same density, there are numerous possibilities for the spatial arrangement of the plantation in the management unit, that must take into account the cultivation antecedent, the present species, the regrowth dynamics, etc. Finally, plantation density modifies the vulnerability of young stands to biotic and abiotic hazards, and it is therefore not possible to propose any simple answer for a generalised increase or decrease, regardless of the threats.

4.4.2 How should mixed plantations be established and managed?

In a context marked by uncertainty and change, the creation of **mixed stands** offers a number of potential advantages over the corresponding monocultures: broader range of ecosystem services, frequently higher relative yield, often greater stability, resilience and flexibility. At present, practitioners have few tools for establishing these complex stands, which is an obstacle to their development.

An analysis of reference papers and literature reviews on the functioning of mixed stands leads to the identification of three main principles that should guide the establishment of mixed stands (Bauhus *et al*., 2017).

Firstly, the **objective of the established mix** and the role of the constituent species must be defined. The mixture can have different goals: facilitate the establishment of a target species; optimise the silviculture of the target species by mixing them with companion species; establish a mixture of target species including, where appropriate, main and companion species.

Secondly, it is important to carefully consider the **number**, **compatibility** and **complementarity of the companion species**. The beneficial effect on production can be achieved with a limited number of species (two or three). The species must be chosen based on the compatibility of the silvicultural cycles of the species, so as to avoid an early exclusion of some species, and benefit as best as possible from positive effects in terms of growth, wood quality, reduced biotic and abiotic risks, and reduce environmental constraints.

Thirdly and finally, the **establishment of species** will need to be adjusted **in space and time**. This strategy intends to minimise competition and maximise positive inter-species interactions, starting at the establishment phase, thereby reducing the complexity and recurrence of subsequent management operations.

4.4.3 What silvicultural treatments can be used to restore stands devastated by storms?

The management of forest stands damaged by storms requires restoration strategies adapted to the specific conditions of these situations: unplanned nature of the event, presence of entangled trees, presence of a large amount of slash, sudden drop of the owner's financial assets, high demand for reforestation equipment and technical operators. A scientific and technical literature review was conducted to assess the main silvicultural options available in such situations.

In most cases, a spontaneous regeneration process takes place after a storm. Nevertheless, economic expectations may lead managers to accelerate or even transform natural succession in order to establish a stand that meets management objectives more quickly. The four main types of post-storm restoration strategy, in order of increasing intensity of silvicultural intervention, are: **stand without silvicultural operations**, **natural regeneration**, **enrichment** and **full plantation**.

It is important to carry out a simple and rapid **diagnosis** of the post-storm situation to be able to guide silvicultural choices. The choice of restoration method depends on the potential of the site, the potential ability of the species present to adapt to climate change, the condition of the affected forest plot, and various factors "external" to the ecosystem, such as technical, administrative and regulatory conditions or the owner's objectives. Special attention must be afforded to logging, to the management of surviving trees, the management of slash, the development of companion vegetation, and the status of the silvo-cynegetic equilibrium.

Major storms can affect large areas and, in such situations, restoration represents a window of opportunity to adapt forests to future conditions (climatic and societal). The choice of a restoration strategy must take into account state-of-the art thinking on the resilience and diversity of forests and their related multifunctionality, which points in particular to the use of mixed stands.

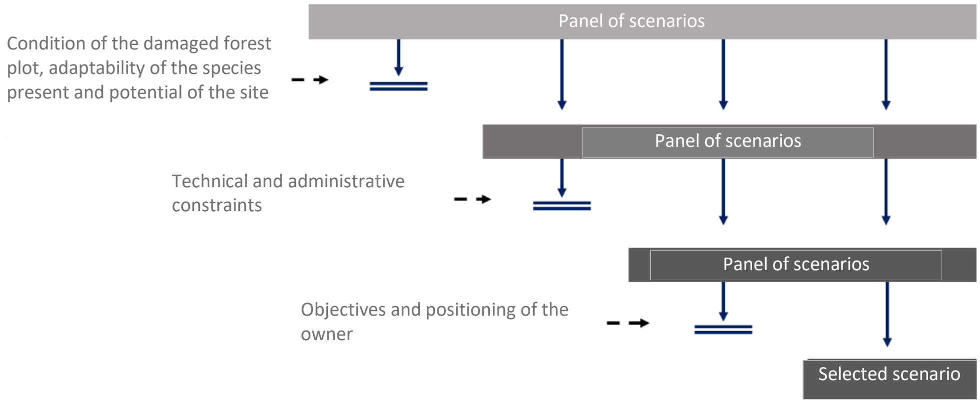


Figure 4-6: Main factors structuring the choice of a restoration scenario

4.4.4 What management protocols can be used to restore forest stands after a bark beetle attack?

The **spruce bark beetle** *(Ips typographus)* is the main pest affecting the European (or Norway) spruce. It has been known for a long time, but the damage observed since 2018 has no equivalent recorded since at least the 1940s-50s[14]. The DSF estimates that 20 Mm^3 of bark beetle-killed deadwood were harvested over the period 2018-2021 in the North-East, i.e. a third of the standing volume of spruce stands located at altitudes below 800 m in this region (Saintonge *et al.*, 2023b).

Similar episodes can be expected in the future because (i) summers will be hotter and drier as a result of global warming, which favours outbreaks of bark beetles (in particular due to a higher number of annual generations) and lower resistance of trees to parasitic attacks; (ii) storms, but also medium-intensity winds such as those that caused scattered damage in 2018 (Gardiner, personal communication), are major factors triggering outbreaks; and (iii) rapid harvesting of bark beetle-killed trees - the only control method proven effective over the past few decades (Marini *et al.*, 2017) - is virtually no longer used due to the widespread use of mechanised harvesting using fellers (that are not used for scattered trees or clumps), whereas until the early 2000s, tractor-skidders still worked in association with human loggers.

Large areas of bark beetle-affected wood, such as those that need to be managed following recent outbreaks, will therefore have to be restored until all vulnerable spruce stand areas are cleansed. Among the solutions available, it is possible to opt for a plantation, by replacing spruce with a species better suited to the current and future climatic conditions or, in order to take into account the uncertainties about the extent of climate change, to opt for a mixture of species which will, in principle, provide production alternatives and the conservation of a forest environment in the event of the mass dieback of a species. Restoration may be carried out by (i) **planting several species** over the entire area to be restored, (ii) use existing **natural regeneration** by favouring the coexistence of multiple species,

[14] Foresters still remember that immediately after the Second World War, dry summers (particularly in 1949) caused considerable damage, particularly in the Vosges region, due to the lack of pest no control at that time.

or (iii) **enriching** the natural regeneration by planting species complementary to those that appeared spontaneously.

If the bark beetle-killed deadwood has not been felled quickly (about 1 year after the bark beetle attack) and is degraded, which reduces its economic value, the option of **not intervening**, without felling or extracting trees attacked by beetles, would present the advantage of (i) avoiding the need to harvest and clean up the plot, (ii) preserving the soil (no compaction by machinery), and (iii) providing some protection for natural regeneration against deer browsing (thanks to dead trees that gradually collapse). Conversely, this solution also increases the risks (forest fires, safety for wanderers due to falling trees) (Hlásny *et al*., 2019). Such an option should be restricted, where appropriate, to areas where spruce regeneration is not abundant if spruce succession is ruled out.

The various regeneration pathways, with or without slash harvesting, and their conditions of application are detailed in the guide to implement mixed regeneration, based on the principles of mixed Continuous Cover Forestry (Laurent *et al*., 2022). Generally speaking, the method of restoration will depend on the nature of the existing natural regeneration but, most of all, on the resources available to the forest owner to manage the mixture during stand development (id.). Experimental and monitoring networks are being set up to test restoration protocols and assess the extent to which they meet the owner's objectives, such as the EGIDE project's *Observatoire des Reconstitutions Mélangées post-Scolytes* (established in 2023 and 2024), which will complement an analysis of the approaches implemented in neighbouring countries, some of which have been hit even harder by bark beetles.

4.4.5 What forest management protocols can be used to restore stands after a fire?

In France forest fires have historically involved primarily the Mediterranean and South-West regions. After a forest fire, there is generally strong public pressure to quickly restore the damaged stands. The various options available for restoration were explored based on experience capitalisation research on post-fire management by forestry management players.

The choice of a stand restoration strategy begins by considering the **objectives** pursued by the **restoration**, generally related to the protection of natural environments, actions included in the Defence of Forests Against Fires (DFCI) initiative, preservation of landscape quality, preservation of biodiversity, forestry production and carbon sequestration.

Next, it is necessary to assess the capacity of the forest flora to recover through **spontaneous dynamics**. This assessment involves an expert analysis of the characteristics of existing stands, as well as of all factors likely to influence their restoration. The diagnosis is based on an assessment of the severity of the fire, the history of the stand and site characteristics, and takes into account the size and shape of the burned areas.

The **management protocol** is chosen according to the capacity for spontaneous restoration and the restoration objectives. The felling of burnt timber, often carried out for landscaping reasons or to secure the site, must be considered in terms of its potential impact on the soil and on regeneration, as well as on biodiversity. The level of intervention for restoration can vary, with increasing intensity, from simple monitoring of natural restoration, to measures to boost natural dynamics, through to restoration by reforestation. The intensity of the fire, its recurrence, the potential of seed trees, the site conditions and competition from spontaneous vegetation, as well as the owners' objectives, constraints linked to climate change and the browsing pressure are all factors that will influence the technical choices.

Selected bibliographical reference: Moreira *et al.* (2012)

4.4.6 How diversified are the forest renewal initiatives tested in the regions? Could they be useful to back up a thinking process about diversifying renewal practices?

The choice of a regeneration pathway to be favoured in the context of climate change must be guided by recommendations verified by field observations. These recommendations can be based on experiments set up with a scientific protocol and on **renewal initiatives in test plots**. A survey has provided an initial overview of the renewal initiatives implemented by R&D players over the past 20 years in France. This review focused on alternatives to even-aged, dense, single-species plantation after clearcutting and/or initiatives designed to cope with various climate change constraints.

A total of 143 initiatives reported by the CNPF, ONF, forestry cooperatives, Chambers of Agriculture and forest owners have been identified throughout France. Among them, 60 initiatives were selected for further characterisation.

The engagement of survey respondents reflects a strong concern for finding alternatives to the most common practices to date and to share experience. There is considerable interest shown for introducing **species mixtures**. The planting designs are sometimes complex (varying density, combination of planted and naturally regenerated areas, spatial patterns associating several species differently, etc.). One of the difficulties of this survey resides in characterising the initiatives, and it was necessary to clarify the vocabulary used (Bastien & Gauberville, 2011). This survey, which will lead to the production of a catalogue, will serve as a **working reference** for future work. It could give rise to an in-depth analysis of the value of the approaches identified, and point to some establishment designs that could be tested usefully in the field.

4.4.7 What are the recent and expected developments in Europe in the field of forest stand renewal in the context of climate change?

Climate change is prompting forestry players to question their forest renewal practices. A **consultation of European experts** on recent and expected developments in regeneration methods was organised as part of the CRREF assessment. The survey was backed by the European Institute of Planted Forests (IEFC), who contacted by e-mail more than 130 professionals (researchers, academics, managers and heads of forestry administrations or services) from its network throughout Europe (21 countries). Given the resources and deadlines allocated to this task, it was not possible to carry out a full stratified sampling and to involve civil society stakeholders in each country.

Experts from the following **ten countries** responded: Norway, Sweden, Netherlands, Germany, Czech Republic, Switzerland, United Kingdom, Ireland, Spain, Portugal. It is therefore essentially a north-south gradient, from Scandinavia to Portugal, that was documented. Half of the respondents were researchers, while the others were mostly forest managers (private or public).

The main findings of the survey are as follows:

- The data collected on **alternatives to traditional plantation** are limited and relatively poor. This is likely due more to a lack of information on the part of respondents than to a lack of initiatives in this area, but this cannot be verified.
- The causes of **plantation failure** after clearcutting seem fairly classic (pine weevil, large ungulates, etc.), with only one mention of problems linked to the reforestation surface area following large-scale health problems.

- The system for **monitoring the plantation success** implemented in France by the DSF does not appear to have any equivalent in other countries. The Swedish system, the only standardised tool mentioned, is not limited to the 1st year after planting, unlike the French system.
- Regions where **natural regeneration** is increasing seem to correspond more to situations of sharp disturbance rather than to deliberate choice. Elsewhere, the role of **artificial regeneration** is increasing in line with the need to adapt forests to climate change.

While the practice of clearcutting is criticized by civil society in many countries (Sotirov *et al.*, 2022), no clear decline in clearcutting practices seems to be observed in countries with a large forestry economy. There might in fact be opposite shifts, one towards more continuous cover forestry in certain conditions, and the other towards more plantations and clearcutting.

Part 5 | Cross-cutting issues

The CRREF expert assessment was carried out by addressing the topics of clearcutting/renewal system and of stand renewal in the context of climate change largely independently of each other, which may sometimes seem to lead to paradoxes.

The purpose of this section is to explain and briefly discuss certain divergences by looking at two issues: (1) Issues raised by the implementation of "active" adaptation to climate change for forest ecosystem conservation policy, and (2) how to reconcile the implementation of "intensive" silviculture with the preservation of forest ecosystems managed in this manner.

5.1 Accelerated adaptation to climate change (in particular, choice of tree species for the future) *versus* forest ecosystem conservation policy

The CRREF assessment report highlights the contradictions between the **need to renew stands by planting** and the need to **take into account the negative impacts of clearcutting and plantations on forest biodiversity**. For instance, some conclude on one side that in order to conserve forest biodiversity, it is preferable to promote natural regeneration, reduce the amount of plantations, and restrict the use of exotic species, but without taking into account the issue of climate change, notably because the subject is complex, the analysis is complicated and the availability of findings is poor. On the other side, the adaptation of forests to climate change, which aims to limit dieback and health problems, retain wood cover, and ensure the supply of quality timber in the medium to long term, is pushing the forestry & timber industry to create right now the conditions for retaining the wood canopy and guaranteeing the wood supply, by applying more "interventionist" methods of stand management and renewal.

Both concerns are legitimate, but each has its own limitations. Indeed, reasoning about tomorrow's forest management under the constraint of climate change without considering the entire forest ecosystem and its biodiversity, or recommending silvicultural choices that favour biodiversity without taking into account the effects of climate change on forest stands and biodiversity, do not constitute thorough approaches.

These issues are thus addressed incompletely by considering the relationships between only two of the three compartments, "climate change", "forest management" and "biodiversity", and analysing:

- either (1) the effects of climate change on trees and forest stands, with the aim of identifying avenues to adapt forest management to climate change,
- or (2) the impacts of forest management on associated biodiversity, with the aim of providing recommendations for more biodiversity-friendly forest management,
- or (3) the effects of climate change on (non-woody) biodiversity, with the aim of assessing the shifts in species' distribution areas induced by a rise in temperature or a change in rainfall patterns.

However, in each case, the analysis overlooks the effects induced by - or on - the third compartment.

In other words, it is important to step beyond these partial visions and adopt a more integrated vision that will consider the triptych "climate change, forest management and biodiversity conservation". Adaptation actually concerns also biodiversity and all aspects of forestry.

For instance, the strategies to adapt forestry to climate change, which propose increasing the level of wood harvesting, shortening the length of silvicultural cycles and increasing the density of forest roads in order to respond faster to crises, are questionable because they are not compatible with a forest management favourable to biodiversity. Conversely, promoting virtuous forest management in terms of biodiversity without taking into account the effects of climate change on the distribution of forest species can lead to dead-ends if the forest habitat that hosts the biodiversity to be protected is likely to disappear according to future climate projections. Thus, a study conducted in a large forest in the Loire and Allier regions (with the goal of isolating the specific role of climate-induced changes in species composition within the overall effects of climate change) indicates that the amount of habitat available for certain species of forest birds by 2050 (preferentially associated with specific tree species) may be much more influenced by changes in tree species composition induced by climate change than by direct changes linked to variations in the birds' climate envelope (Lalechère and Bergès, 2022). It is therefore crucial to understand how climate indirectly modifies the distribution of dominant vegetation and to clearly grasp the cascading effects of climate change on species dynamics (Titeux *et al.*, 2016; He *et al*., 2019). A key point lies in our lack of knowledge on the ability of forest stands to adapt to climate change, meaning that there is no certainty that all stands located outside the predicted future areas will disappear as quickly and massively as the models predict. Similarly, species habitat models rarely take into account the ability of animal species to adapt to changes in the resources available in their environment following a change in their habitat. Furthermore, in their fear of seeing all productive forests collapse, public authorities and the forestry & wood industry may opt for very "interventionist" strategies, and go beyond the most pessimistic forecasts of climate models, even if it means repeating some of the mistakes of the past (without forgetting that the management of plantations, with their possible failures, and of exotics is subject to difficulties). Conversely, given the speed of climate change, which is far greater than the migration capacity of many species (Loarie *et al.*, 2009), assisted migration of species (woody and others) should be considered to ensure their conservation in the medium term (Vitt *et al*., 2010), even if the relevance of assisted migration is still the subject of debate (Hewitt *et al*., 2011; Loss *et al.*, 2011).

Finally, a fourth dimension that must be taken into account in this type of trade-off is the role of the forest in regulating the climate in the short to medium term, through the storage of carbon *in situ*. Thus, the conservation of forest ecosystems can be understood not only as the preservation of biodiversity, but also as the development of the carbon stock in the soil (in particular for retention of the canopy) and the stand (e.g. more large trees). This additional dimension however goes relatively hand in hand with biodiversity conservation, i.e. practices that promote soil and stand carbon sequestering are generally biodiversity-friendly (Pichancourt *et al.*, 2014; Di Marco *et al*., 2018).

In order to propose forest management and stand renewal methods that meet the dual challenge of adaptation to climate change and preservation of biodiversity, the solution is not just "technical", but involves making progress as quickly as possible in a number of areas to fill in the gaps in our knowledge of the direct and indirect effects of climate change on forest ecosystems and their biodiversity: (1) Continue improving predictive models of the response of forest species to future climates, taking into account all ecophysiological processes (mortality, adaptability of stands to environmental changes, dispersal of individuals); (2) reduce the levels of uncertainty in predictive models; and (3) continue and expand experiments on the response of plants (woody and non-woody) to climate change *(ex* and *in situ*, comparative plantations, etc.).

5.2 Mechanised silviculture and forest ecosystem conservation issues

The clearcut/plantation system makes extensive use of **mechanised silviculture** to carry out various operations: harvesting mature trees (felling, hauling), post-felling slash treatment (removal, shredding, possibly windrowing or stumping), mechanical site preparation (MSP), maintenance of skid roads, clearing and tending operations. For each of these operations, mechanisation aims at facilitating the operation, reducing costs and reducing physically demanding work. In the case of mechanical site preparation, a significant improvement in seedling survival and initial growth is observed, particularly in years with intense summer droughts and in situations of high competition from neighbouring vegetation.

The main limitations of mechanisation is that it entails proven risks of ecosystem degradation, and in particular of the physical, chemical and biological properties (including carbon loss) of the soil. While the mechanisation of forestry practices is likely to increase in the coming years, this shift will require the development and implementation of methods that respect the soil and its biodiversity, for logging, planting and other silvicultural works.

In France, these issues were addressed after the storms of 1999, initially during the **operational phase**, and led to the publication of the Prosol (Pisccheda, 2009) and Pratic'sols (Augoyard *et al.*, 2021) guides, proposing a series of recommendations: strict regulation of machinery traffic in stands according to the sensitivity of the soil to compaction, installing permanent skid roads and limiting the weight of machinery. More recently, the sequence of harvesting, clearing, reforestation and tending operations has been questioned as their overall on soil and biodiversity are presently unknown. The linkage between these operations has to be improved, and must be considered as part of an overall sylvicultural system. The main challenges are:

(1) Reduce as much as possible the traffic area, which may be compacted by the machines entering the stand. In particular, this means retaining the location of skid roads at all stages in the life of the stand and between two successive generations of stands, with permanent markings (e.g. high stumps or stakes) in the plots or by tagging via a GIS system coupled with the use of GPS on the machines. The feasibility of these methods is currently being assessed in various regions.
(2) Reduce post-felling operations such as shredding, windrowing and stumping, which requires designing alternative reforestation methods. The *Eco-Reboisement* (eco-reforestation) method developed by the *Coopérative Forestière Bourgogne Limousin* is an example of this type of integrated protocol.

Research on MSP conducted since the mid-20th century have mainly focused on the technical and economic performance of the methods, while their environmental and social dimensions have only recently been taken into consideration. In the current and future climate conditions, hot and dry summers increase the risk of plantation failure, especially when competition from neighbouring vegetation or soil compaction are high. In such conditions, MSP is seen as an essential tool to ensure successful seedling establishment, and plantation success is generally correlated positively with the intensity of the work carried out (which may be estimated by the volume of soil tillage, or the quantity of vegetation controlled) unless it is carried out in wet conditions. These operations can be perfomed in a limited area around the seedling (50 to 100 cm), which reduces considerably soil disturbance at stand level, compared with a preparation carried out over the entire stand surface. These observations suggest performing intensive but very localised MSP, typically individual spots, or patches of 9 to 25 seedlings, in order to leave the rest of the stand intact. In addition, it is crucial to avoid carrying out this preparation in wet soil conditions, to use light-weight machinery, and to limit movements within the stand, in order to minimise soil compaction and rutting. It should be noted that beyond these very general recommendations, there is currently no operational guidelines for choosing the tools and selecting the conditions when MSP may be performed while maintaining soil integrity. Furthermore, in current practice, the availability of machinery and drivers and the organisation of forestry campaigns do not guarantee compliance with the general recommendations, and many MSP are performed in conditions where the soil is sensitive to the stresses induced by mechanisation.

At present, mechanisation of plantation **cleaning and tending operations** are limited in France, but the need to reduce physically demanding work, the demand for more highly-skilled jobs and the increasing labour shortages are all driving an increase in the mechanisation of these operations. As with MSP, mechanisation of cleaning and tending operations will require the development of light-weight, agile machines that perform localised work, in order to reduce their impact on soil physical and biological qualities and thus sustain future stand productivity.

Finally, when choosing a regeneration strategy, it is important to compare the options available to renew the stand, which range along a gradient of management intensity from natural regeneration to enrichment planting and full planting. To this purpose, the site ability to naturally regenerate and its sensitivity to mechanised operations must be estimated, and planting should be restricted to situations where natural regeneration does not enable management objectives to be met and where local conditions (site characteristics, organisation of the worksite, availability of operators, etc.) make it possible to carry out reforestation operations that respect the soil. In other situations, protocols using natural regeneration and minimising mechanised intervention should be preferred. To implement this approach, tools for diagnosing the regeneration potential and sensitivity of soils to MSP, as well as **practical guides** for implementing soil-friendly mechanisation during **reforestation**, need to be made available to forestry practitioners.

Conclusions

Main scientific and technical findings

Definition of clearcutting

Historically, foresters in France have been using the vernacular term "*coupe rase*" (clearcut/clearcutting/clear felling) since World War I, while the term "*coupe à blanc-étoc*" had been used in France since at least the King's Ordinance of 1669 to designate originally a tree felling method, and later the felling of a given area, whether a coppice or a high forest .

The proposed **silvicultural definition** of clearcutting is close to the definitions most commonly used, i.e. "a cut that removes nearly all trees in the stand at once, leaving the ground mostly bare (with no herbaceous or woody vegetation higher than approximately 50 cm) before the stand is regenerated, usually artificially".

From an **ecological** standpoint, the analysis of microclimatic and biogeochemical criteria does not enable a precise threshold to be proposed for the clearcut area below which there would be no significant functional disturbance but the levels mentioned seem to be well below the 0.5 ha threshold generally used in silviculture as the limit between the even-aged high forest (in patches) and the uneven-aged high forest (in clumps) systems.

Finally, from a **legal** standpoint, jurists as well as environmental NGOs and the general public may find the proposed silvicultural definition inadequate and could argue that it would be legitimate to adopt a clearer "impact-based" rationale in view of the issues identified in this assessment. The challenge would then be to determine whether these impacts are significant, reversible and temporary or permanent, and whether or not they require avoidance, impact mitigation or offsetting measures.

Assessing and monitoring clearcuts and other types of canopy loss

In the **1980s**, the IFN estimated the annual clearcut surface area in mainland France at 31,100 hectares, with an average unit size of 4 ha. When adding other types of felling that remove more than 90% of the canopy (mainly final felling as part of natural regeneration), the area concerned was estimated at 67,900 ha/year. Clearcuts accounted for just under half of the fellings that removed more than 90% of the canopy.

For the period **2011-2020**, the level of clearcutting cannot be evaluated due to a change in the IFN census method. The surface area of fellings that removed more than 90% of the canopy totalled 67,800 ha. Overall, no significant change therefore seems to have taken place over a 30-year period, but caution is advisable due to changes in methodology.

There are major **regional disparities** in terms of fellings removing more than 90% of the canopy. The New Aquitaine region currently accounts for half of all clearcuts in France, as (i) clearcutting is predominant in this region, and (ii) the species concerned (mostly maritime pine) have a short rotation. In large forest regions such as the Grand-Est, which are subject to regular felling, but where the species concerned (oak, beech, etc.) have a longer rotation and where even-aged high forest is less dominant (due to the importance of coppice/high forest mix and uneven-aged high forest), this rate is five times lower than in New Aquitaine. Finally, this ratio is minimal in regions where there is almost no forest exploitation, sometimes over a fairly long period (Provence-Alpes-Côte d'Azur, Corsica). Locally, even more disparate situations are observed when the fellings tend to be repeated year after year in the same areas. This is the case in the Morvan region, for instance.

One of the most significant developments since the 1980s in private forests has been the increase in clearcutting in forests managed under the “Simple Management Plan” (PSG), linked to the transformation of sparse tree stands. Conversely, a sharp drop is observed in the proportion of clear- and heavy felling in **public forests**. Recent years have also been marked by the growing importance of **health issues**. Damage to spruce (bark beetles) has been well documented by satellite imaging (Theia Service, INRAE) and on the ground (by the ONF, field database). Major damage to chestnut trees has been observed in private forests.

A major difficulty in interpreting the data available is that ground monitoring by the IFN and aerial or satellite monitoring (remote sensing) detect tree cover losses resulting from clearcutting or heavy felling, but also (in varying proportions over time) from mortality or disturbance due to disease, fire, climate hazards, land clearance, etc.

The evaluation of canopy losses by **satellite imaging** in recent years (2017-2021) indicates (i) a picture that is generally consistent between the monitoring carried out at national level (Théia service, INRAE) and at global level (Hansen *et al.*, 2013) (70,000 ha/year), and (ii) estimates of areas harvested annually that are consistent between aerial surveillance and ground monitoring by the IFN. Approximately 70% of detected canopy losses are less than 4 ha, based on a cross-referencing of satellite and ground data.

The apparent absence of any increase in cuts harvesting over 90% of the canopy is surprising given (i) the gradually complete maturity of National Forest Fund (FFN) plantations, many of which date back to the 1950s-1970s, (ii) the recent development of coppice felling (included in these surveys) for fuelwood, and (iii) the ramp-up of PSG-governed stands in private forests (which sometimes provide for converting the sparsest stands). It may be assumed that opposite trends have been at play, such as a voluntary reduction of clearcutting by some individual forest owners or managers, or the end of clearcutting in the state-owned forests of the Île-de-France region, etc.

Effects of clearcutting on the physical and chemical environment

The main **effects of clearcutting on the physical and chemical environment** are generally well documented, including at our latitudes: (i) generally negative impacts on the structure, chemical fertility and carbon storage of soils, the microclimate and some related risks (windthrow, late frosts, heatwaves), as well as on the quality of watercourses; (ii) their extent varies greatly depending on local conditions (climate, slope, soil texture, etc.) and on the felling and renewal methods; (iii) some impacts may be irreversible (loss of soil through erosion) but generally fade over time, with variable impact durations depending on the process, ranging from a few years to several decades; (iv) impacts increase with the size of the felling area (for sufficiently documented parameters), without any threshold effect (or very low < 1 ha).

Several types of risks are related to clearcutting:

1) **Risks linked to changes in the microclimate close to the ground**: Increase in daily and seasonal temperature amplitudes. The amount of water in the soil increases, except at the surface which dries out faster. These effects are also perceptible in uncut areas, up to 100 m from the edge in terms of air temperature or moisture, as well as in gaps (< 0.25 ha), but more so at extreme values, and may last for several years after felling. Studies suggest that these effects will be amplified by global warming. Small-size cuts minimise freezing temperatures and water or thermal stress for seedlings and young trees; thus, even for species regarded as “shade intolerant”, there seems to be an optimum felling size for the survival and growth of juveniles, which optimises their needs in terms of light as well as water and nutrients.

2) **Risk of windthrow**: When a gap is larger than two or three times the height of the tree (0.25 ha for 20 m-high trees), the risks of windfall in neighbouring stands during storms increase considerably, especially if the number of newly created edges in relation to the wooded area is high and if these edges are far from stable edges (roads, power lines, etc.).
3) **Risks of erosion and rising water table**: Within 3 to 5 years after felling, the reduced evapotranspiration and interception lead to an increase of water in the soil, a rise in the water table and an increase in surface runoff, thereby significantly increasing the risk of soil erosion in some situations.
4) **Potential loss of chemical fertility of the soil**, with a possible deterioration in the chemical quality of watercourses: these effects are linked to the removal of nutrients from the ecosystem via the harvested biomass, especially in the case of foliage or brushwood harvesting. In addition, clearcutting leads to a significant input of plant debris on the ground, which releases nitrates and nutrient cations when decaying. In the absence of vegetation capable of absorbing these elements, they are likely to be leached from the soil and exported to watercourses over a period of up to 5 years.
5) **Soil carbon loss**: This mostly affects the surface horizons, with an average loss of around 5-7% of the total soil organic carbon stock, with broad variations from one site to another and greater losses where whole trees and stumps are harvested. Carbon loss increases in fine (clayey) textures and reaches an average of 21% of the carbon stock in the surface layer with pre-planting soil preparation, compared with 9% without preparation. Replenishing the soil's carbon stock after renewal can take several decades.

Furthermore, the **mechanised harvesting operations** associated with clearcutting increase some of these effects. Machines compact the ground from the very first passage, especially if the clear-felling takes place on wet soil. This compaction hinders rooting and rainwater infiltration, leading to a reduction in soil aeration at the surface and even to temporary waterlogging (particularly in lowlands), which can cause the failure of future plantations. It also leads to an increase in run-off and the related risks of soil erosion (mainly on slopes).

Other practices help to mitigate the effects (logging partitions, tree retention, natural regeneration), or on the contrary, exacerbate them (brushwood harvesting, windrowing, stump removal, mechanised soil preparation).

Effects of clearcutting on biodiversity

Data in the literature on this subject address mainly boreal zones and North America in the case of temperate zones. Although the mechanisms they describe can probably be transposed to the temperate forests of mainland France, some caution is required when extrapolating these data to the conditions of European temperate zones, and to French conditions in particular.

Impact of clearcutting *stricto sensu*

At **stand** level, the effects of clearcutting are generally positive in the short term for open-habitat species, and last about a decade, but become negative in the medium (20 to 50 years) and long term (> 50 years) for all taxa, and in particular for mature forest specialist species, compared with unharvested stands. In comparison, shelterwood regeneration cuts tend to host more species, but this is a low and non-significant trend, which is not sufficient to avoid these negative effects in the long term. Furthermore, in uneven-aged treatments (selection cuts), the stands did not differ statistically from the controls. This is why an increase in the proportion of uneven-aged or long time unmanaged forest stands, which are currently a minority in France, seems to be an interesting option, although it is not possible yet to specify the ideal "mix" at landscape level. The contrasted effects between the two scales must be taken into account: while uneven-aged felling is favourable for biodiversity at stand level, its widespread use could homogenise habitats and reduce biodiversity at landscape level.

On the **landscape** scale, all felling areas combined (1-70 ha) and all ecological groups combined, clearcutting has a negative effect on the number of bird and bryophyte species, but non-significant on vascular plants, lichens, fungi, arachnids and insects. As the size of clearcutting area increases, the negative effects increase (birds) and the positive effects decrease (plants). However, there is a lack of data and dedicated studies to suggest possible **area size thresholds**. In addition, it is unknown which **spatial distribution** of clearcuts in the landscape would be least unfavourable to forest biodiversity (many small patches versus a few large ones).

Other notable effects of clearcutting include:

1) The **edge** effect which extends the effect of clearcutting beyond its boundaries over a few metres and up to 200 m depending on the taxon and the context; forest species are pushed back towards the forest interior, while non-forest species can penetrate into the forest interior, at least in the short term. The edge effect also manifests itself in the other direction, through the recolonisation of forest species in the clearcut.
2) Biodiversity of **riparian forests** and the aquatic biodiversity of the watercourses along which they run are negatively impacted by clearcutting near watercourses, over a range up to 100 m on either side of the watercourse.
3) The impact on **soil biodiversity** varies greatly depending on the taxon: in the short term, a change in fungal communities, and a reduction in microbial biomass and in fungus/bacteria ratio are observed. Clearcutting has a sharp impact on the composition of the macrofauna, but less so on the mesofauna. Root colonisation by ectomycorrhizae is facilitated by the proximity of forest edges and the retention of woody regrowth.
4) Influence on **wild ungulates** due to the availability of abundant and palatable feed sources. This can lead to an increase in herbivorous ungulate populations and a change in their spatial distribution, with consequences for plant diversity via the mechanisms of herbivory and zoochory.
5) **Replacement habitats** provided for **species from open and farming environments**, in regions where agriculture has intensified and semi-natural grasslands have declined sharply.

Impact of clearcutting according to forestry management methods

Slash retention has variable effects in the short and medium term, depending on the site and the taxa, but generally has a positive impact on plant diversity, saproxylic insects, fungi and lichens, and wood growth. It prevents the spread of invasive or generalist flora and fauna species.

Mechanised **windrowing** of slash or stumps impoverishes flora communities, and fosters non-native or invasive species, small mammals and their mustelid predators.

Stump removal has a greater negative impact than brushwood debris harvesting, particularly on saproxylic insects.

The **deliberate retention of habitat trees** (>10 to 15%, scattered or in clumps) provides a host environment for richer communities in the short and medium term, but is insufficient to preserve the richness of forest specialist species in closed-canopy stands over the long term (> 50 years). The positive effect of retention increases with the proportion of retained trees in the clearcut.

Impact of post-clearcutting sequences (mechanised soil preparation, planting versus regeneration)

At stand level, **mechanised soil preparation** prior to planting fosters woody plants and reduces flora richness in the short term. It reduces the richness in ectomycorrhizae, the abundance of the main soil fauna taxa (in some cases durably) and of microbial and fungal communities. The resulting change in the ectomycorrhizae/saprotrophs ratio can disrupt the decay of organic matter in the short term. **Plantations** generally lead to reduced biodiversity, or at least to changes in its composition, particularly to the detriment of native species. These negative effects may subside over time, but not always. Choosing **native** rather than **exotic species**, and mixed rather than pure plantings, helps to mitigate the negative effects of plantations, without however cancelling them out entirely.

On a landscape scale, the introduction of an **exotic species** can enhance species richness by bringing in species that are new to the region, but this effect is limited because the diversity associated with a species increases with the length of time it has lived in an area, and therefore with potential co-evolution; exotic species host a lower and more generalist biodiversity than native species. Furthermore, the introduction of an exotic species can bring with it other exotic companion species (including pathogens) and alter the genetic diversity of genetically close native species.

Human, social and economic dimensions

The practice of clearcutting was extended to high forests as early as the 15th century to improve the **supervision of felling** by the Forestry Administration. With the development of silviculture, the conversion of coppice into high forest and, for the latter, the “**method of natural reseeding and thinning”** were pushed to the forefront. More recently, plantations to protect coastal and mountain soils have paved the way for **production plantations** and a return to clearcutting alongside traditional forestry practices. Today, clearcutting is partly linked to the behaviour of species (shade-intolerant species), adaptation to the site and to climate change, for economic reasons (productivity, cost reduction), streamlining operations (logging, renewal, management, monitoring, etc.), and disaster crisis management (biotic or abiotic crises) and/or natural regeneration failures.

A recurring subject of social tensions since the 19th century, clearcutting has nonetheless prompted an increase in **public mobilisations** since the 1970s, with a near-exponential rise since 2015, despite an apparent stability of clearcut areas since the 1980s. Clearcutting is therefore a renewed source of conflict between producers and users. The **arguments** against clearcutting are traditionally landscape-related, but are increasingly ecological and economic in nature. For foresters who carry out clearcutting, this operation optimises the harvest from a technical, logistical and economic standpoint. They consider that clearcutting has its place in a mosaic that is potentially beneficial from a landscape and ecological standpoint. Against the aggregate national indicators (around 70,000 ha/year of felling having removed over 90% of the canopy for 17 million ha of forest cover), opponents object the concrete experience of the inhabitants in areas where these felling operations are practiced and their c**umulative effects over short time periods** on the quality of the living environment and ecosystems.

Conflicts over clearcutting are therefore both rooted into particular silvicultural situations, and also closely linked to the major forestry debates and policies currently underway. They illustrate the discrepancy between the values that different social groups project onto forest areas, whether in terms of respect for ecological cycles, the need for economic profitability or the preservation of the living environment. Clearcutting thus becomes an indicator of social change and a banner for more fundamental demands about the meaning of forestry production, its optimisation and its contribution to territorial development, and the methods of forestry governance, etc. It is important, however, to distinguish between the substance of the grievances at play, i.e. the substantive dimension of what causes the problem, and the more or less demonstrative form that the protagonists resort to in order to publicize their cause in the public arena. Given the present level of conflict about clearcutting, rarely reached in the past, these protests attest to a strong determination on the part of environmental NGOs and citizens' groups to influence the **debates on the role of the forest and its current management methods**. They federate and give visibility to protests that have existed in some regions for over 20 years sometimes, but had difficulty making themselves heard beyond local spheres of debate. By channelling the protests, the dominant players in the sector had managed to more or less maintain the broad outlines of the forestry social order. But in recent years, the coordination and professionalisation of activist groups, the development of innovative protest tools and their growing advocacy expertise have given a new impetus to these movements, which are using the same strategies as their opponents, namely direct contact with the political and administrative sphere and putting it under regular pressure. Ultimately, the resolution of these conflicts will depend in part on how the discussion mechanisms are organised and on the willingness of the various protagonists to reach fair and equitable agreements for all. In the meantime, some foresters' groups are already changing their practices in the field by lowering clearcutting thresholds or even abandoning it altogether. The current protests against clearcutting are probably speeding up these adaptations as much as they are opening up new areas for questioning the relationship between forests, foresters and society.

In the current context, the **issue of a regulatory framework for clearcutting** has become particularly acute. One of the debated points is the benefit of thresholds beyond which clearcutting could or should be banned. There is currently no national definition or regulatory framework for clearcutting, either in private forests or in forests covered by the national Forestry Regime. The approval by the public authorities of a Sustainable Management Document (DGD[15]) means that forest owners do not have to follow any other procedure. The only regulatory requirement following clearcutting concerns reforestation (art. L.124-6). This provision requires foresters to reforest within five years after clearcutting or harvesting an area exceeding a size threshold set by the Department Prefect. A threshold, generally between 0.5 and 4 ha, is set at Department level by the Prefect for felling removing over 50% of the volume of trees in the forest (art. L.124-5).

Several measures are already being implemented to reduce the use of clearcutting. As an example, a reduction in the size threshold for clearcut areas is under consideration as part of the revision of the *Schémas Régionaux de Gestion Sylvicole* (SRGS, or Regional Forestry Management Master Plans) and of the specifications for certification schemes.

The ***Schémas Régionaux de Gestion Sylvicole*** (SRGS[16]) are currently being revised, and some are in the process of being approved. Size thresholds beyond which clearcutting would be prohibited or subject to conditions are under discussion.

The two **forest management certification schemes** in force (PEFC and FSC) contain two sets of specifications that address clearcutting in particular. Revisions of the respective requirements have been underway since 2021 and will be completed in 2023. To date, there is no PEFC definition of clearcutting. The PEFC requirements were related to size, limiting clearcuts to between 2 ha and 5 ha on slopes >30%, and 10 ha to 25 ha in other cases, unless documented exception. The FSC standard defines clearcutting and limits its size to 2 ha where the slope is >40%, and to 10 ha in other cases,

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[15] The management documents, drawn up in accordance with regional directives and master plans, are as follows: 1) For woodlands and forests governed under the Forestry Regime: a) Development documents; b) Standard Management Regulations (RTG); 2) For private woodlands and forests: a) Simple Management Plans (PSG); b) Standard Management Regulations (RTG); c) Codes of Best Silvicultural Practices (CBPS).

[16] The SRGS master plan is a document drawn up by the *Centre régional de la propriété forestière* and approved by the *Commission régionale de la forêt et du bois*. It provides management guidelines, recommendations and requirements to be followed for the sustainable management of private forests benefiting from a DGD (Sustainable Management Document).

except in the Landes region where the limit is up to 25 ha. Discussions on the revision of these two reference standards are proposing both definitions and reductions in the size of eligible areas, or even bans in some specific habitats. For PEFC, a definition is proposed as well as bans in forest areas of high ecological value; the size is reduced to 2 ha on slopes, a target is set at 5 ha and any other clearcutting of up to 10 ha must be justified, except in the case of single-species plantations. For FSC, the trend is the same, with bans for certain habitats or conservation networks, and size limits that have not yet been decided but will most likely be slightly higher than current references.

Other options could be explored. Thus in private forests, supervision of clearcutting could be improved by **increasing the DGD-managed areas**; the threshold for the requirement to submit a PSG (Simple Management Plan) could for instance be lowered to 20 ha instead of 25 ha, and the voluntary submission of PSGs as of 10 hectares could be encouraged.

Nevertheless, subjecting clearcuts to systematic authorisation, without either State administrations or the CNPF having the means to investigate and control, seems illusory, because in reality, current regulations do not allow a clearcutting request submitted by individuals who have no DGD to be rejected on grounds of landscape or biodiversity conservation. In order to help investigating administrations, a **matrix based on objective criteria** and validated by the authorities could be provided to enable an objective and shared assessment of approval or rejection decisions. **Lowering the threshold for clearcutting authorisation requests** from 4 to 2 or even 1 hectare by means of Prefectoral decrees governing the authorisation threshold for clearcuts in forests without DGD seems possible, as suggested by an experiment that took place in the Morvan Regional Nature Park in 2021.

At the territory scale, it would be useful to investigate the use of certain tools. The ***Schéma de Cohérence Territorial*** (SCoT[17]), or Territorial Coherence Plan, serves as a reference framework for many sectoral policies, but not for forestry or agriculture. By incorporating these policies, the SCoT plan could become the integrating tool for regional land planning. The ministerial report by Anne-Laure Cattelot (2020) is oriented in this direction by advocating the experimentation of a “local forestry plan”, similar to the SAGE plans in water management. This view is not currently shared by all stakeholders, and in particular by private forest owners and managers, who consider that regulating forest management with SCoT plans and Local Urban Planning schemes could lead to woodlands and forests being regarded essentially from a landscape and environmental perspective, while neglecting their economic production aspects.

Finally, the debates have reached the political arena, leading to a number of **legislative** position statements. The *Convention Citoyenne pour le Climat* (Citizens' Climate Convention, 2020) has proposed banning clearcutting of areas larger than 0.5 ha. In her report (2020), MP Anne-Laure Cattelot also recommends limiting the size of clearcuts to a maximum of 2 hectares, except for health reasons. In 2020, MP Mathilde Panot and several of her colleagues tabled a bill to regulate clearcuts, which was rejected by the National Assembly (French Parliament).

From an **economic standpoint**, two options were evaluated to reduce the use of clearcutting: limiting the size of clearcuts, and shifting the spatio-temporal structure of forest stands towards a continuous-cover uneven-aged high forest. The option of natural regeneration, which staggers felling over time and avoids plantation, was not examined.

The more mechanised the operations, the greater the cost reduction linked to the **worksite size** due to direct fixed costs (transport, logistics, site supervision) and indirect costs (site administration). For

[17] The SCoT is a tool for designing and implementing inter-municipal strategic planning on the scale of a large “*bassin de vie*” (“living basin”) or urban area, as part of a strategic land planning project (PAS or “*Projet d’aménagement stratégique*”). There are 471 SCoT perimeters in France.

a cooperative such as Alliance Forêt Bois, limiting the size of cuts to 5 ha would double the number of logging sites and increase costs per hectare by around 50% in the absence of compensatory measures for logistical worksite organisation. According to the ONF (French National Forestry Office), limiting the size of cuts to 2 ha would double the number of logging sites, but would have little effect on the cost per hectare. An increase in the total costs of forestry operations impacts the forestry contractors, as well as the profitability of silviculture and more generally the creation of value. Although all phenomena cannot be fully quantified, a decline in timber harvesting, an increase of timber imports or other materials, and an increase in carbon dioxide emissions (imports and number of logging sites) can be expected. These estimates of extra direct costs obviously have to be weighed against the indirect costs arising from the impacts of clearcutting on biodiversity and on soil and water quality.

Economic comparisons between even-aged and uneven-aged high forests are based on the economics of natural resources (in this case, mostly wood supply) and environmental economics (taking into account all other ecosystem services, most of which are non-merchantable services). Approximation methods are often used, which complicates the analysis of lessons that might be learned. An analysis of the economic literature suggests that neither system can be advocated preferably over the other. The results depend largely on assumptions and parameters, particularly as regards risks, taking into account all ecosystem services, and the importance attached to the future versus the present. This is also the case for the initial status, inducing a careful choice of the right moment to convert into uneven-aged high forest, while avoiding doing so for young even-aged stands or older stands.

All of the above considerations on the human, social and economic dimensions highlight differences of appreciation depending on the perspective adopted. The current wave of growing protests against clearcutting raises questions about compromises to be found in the context of forest/foresters/society relationships. It suggests that shifts in clearcutting practices and their adaptation to the public mindset as well as to new climatic, technical and economic conditions are probably inevitable.

Renewal of forest stands

The practice of forest renewal will undergo profound changes as a result of climate change which is affecting the way forests function, and evolutions in social expectations which are modifying the objectives assigned to forests. The CRREF expert assessment aimed to analyse the **difficulties encountered in the renewal of stands** at present and in the future, by combining survey data, scientific and technical literature, and expertise. The avenues envisaged to overcome these difficulties are discussed below.

According to IFN estimates, the **area renewed by planting** reached around 45,000 ha/year over the 2015-2020 period. The identity of the species planted is estimated from annual sales of seedlings since 1992: a strong historical dominance of softwoods and a slight increase in hardwoods have been noted in recent years. The three species with the highest sales between 2000 and 2020 were maritime pine (50% of seedlings), Douglas fir (14%) and sessile oak (7%). The fate of the seedlings sold is not known as there is no traceability system to track seedlings from the nursery to the plantation.

The **forestry seedling needs** are expected to rise sharply in the coming years, in particular due to climate change. Some species will be more specifically in high demand. There are currently shortages of seedlings for certain species due to phytosanitary and climatic problems that reduce the production of marketed seeds, but also due to the industry's failure to anticipate its needs in advance. It is vital to anticipate forest managers' needs as best as possible, in order to produce the expected seedlings, while factoring in the time required to harvest the seeds and manage the crops. Otherwise, certain species or provenances will not be available.

The DSF's annual survey on **plantation success** shows that, on average over the 2007-2020 period, 12% of seedlings died during the first year and 18% of plantations were deemed unsuccessful at the end of the first year (i.e. a survival rate under 80%). Mortality varies considerably depending on the species: the lowest survival rates are noted for Douglas fir and sessile oak and the highest for maritime pine. High mortality rates are mainly observed in years and regions marked by severe drought. Climate change is likely to result in an increase in establishment difficulties and in mortality in the first year.

The **transplant shock** is responsible for a significant proportion of seedling mortality in the first year. This is the period after on-site replanting when the seedling has not yet developed a fully functional root system. The first step in reducing this shock is to ensure that the transplanting chain for seedlings is properly controlled, from their nursery environment to their planting site in the forest. The choice of robust species able to withstand adverse weather conditions at a very young age, and the choice of seedlings with biological characteristics that foster their establishment (in particular large size, low stem/root size ratio, and high root growth potential) are critical to the success of the plantation. In addition, various cultivation methods can be used to improve the environment hosting the seedlings. Mechanised site preparation mitigates the risk of transplant stress by improving the soil and reducing competing vegetation. Conversely, plant cover plays a protective role for seedlings in extreme conditions. In arid zones, water management techniques can limit the intensity and duration of water stress during droughts.

Unlike plantation, no estimate is available on the **areas renewed annually by natural regeneration** in France, nor any breakdown of the renewed area by species.

The success rate of natural regeneration in France is relatively unknown. A survey of forest managers showed that between one third and one half of them were unsatisfied with the **quality of the natural regeneration** obtained, as assessed according to stem density, specific composition and woody cover. Recent studies conducted in several major forest contexts regarded as problematic (mountain fir/spruce/beech stands, hydromorphic lowland oak grove, pine stands in the Aquitaine dune forest, Mediterranean oak groves) have shown low levels of natural regeneration, which fail to ensure satisfactory stem recruitment.

Various studies have analysed the **impacts of climate change on natural regeneration** in temperate forests. Fertility (which combines flowering, pollination and fruiting phases) responds to climate change in very different ways depending on the species. On average, it is stimulated by higher temperatures than those currently prevailing. Nevertheless, the variability of annual seed production is expected to increase. Conversely, recruitment (germination, establishment and seedling development phases) is adversely affected by higher temperatures and lower water balances. In the future, recruitment should therefore prove to be a more limiting factor than fertility in many temperate forest ecosystems. Under future climate conditions, **retaining a canopy above and/or around seedlings** could foster recruitment, as the shelter effect provided by the canopy over the seedlings could become predominant over the competitive effects of the canopy, contrary to what has been observed in temperate forests until now.

Whether in plantations or natural regeneration, **biotic aggressors** (insect pests, pathogenic fungi, micromammals, ungulates) are numerous: more than 400 have been identified. However, only about fifteen pose large-scale problems. Climate change may have favourable effects on many of these aggressors, but as the biological cycle of most pests is poorly understood, it is difficult to predict their future impact.

In years to come, forest **disturbances** caused by drought, fire, storms or bioaggressors are likely to be more severe and more frequent, and their consequences (immediate damage, dieback) should increase accordingly. These disturbances have a major impact on renewal: they sharply reduce the number of seed trees able to produce seeds for natural regeneration, drastically change the conditions (abiotic and biotic) for young trees, and pose specific technical difficulties for silvicultural operations in the plots (presence of windfall, standing dead trees, etc.). The desire to favour **spontaneous renewal dynamics** to regenerate stands is often heard; however, this is not always possible (particularly if too few seed trees are present) nor desirable (if the aim is to switch species to reduce the risk of future disturbance).

In addition to the difficulties involved in securing renewals, climate change may require **modifying the type of stand** targeted at the end of the renewal phase, in order to obtain stands that are assumed to be better **adapted both to future constraints and to social expectations**. This adaptation involves working with the species best suited to future conditions, diversifying the specific composition and the vertical and horizontal structure of the stands. There are some recommendations on establishing the targeted stands but at this time they remain general and cannot be transcribed into operational recommendations adapted to the different situations encountered in practice. To this purpose, a catalogue of initiatives evaluating the establishment of atypical stands has been launched, enabling these initiatives to be identified and documented. This catalogue currently lists 143 initiatives in France, which can form an initial basis for an analysis of establishment protocols and can be supplemented later on.

Research prospects

The CRREF expert assessment has highlighted a number of research needs, which are listed here according to the summary outline.

Scoping

- Continue working on the **definition of clearcutting**, in particular by further integrating the various dimensions (silvicultural, social, ecological).
- Produce a **reference corpus** on current forestry practices, including regional variations.

Clearcuts Monitoring

- Improve the remote sensing methods used to assess clearcuts, by promoting cross-referencing with data acquired in the field, in order to produce a **genuine reference base** that can be used among other to back up statistical summaries.
- Develop a **statistical method for clearcut monitoring** that would be backed simultaneously to systems based on field data (IGN first of all) and systems based on remote sensing (INRAE mapping).
- Progress on the **differentiation of the various cuts** (clearcut, sanitation, etc.) by relying on new methodological approaches based on the complementary nature of the various satellite sensors (optical, radar or even lidar) and on the use of more spatially-resolved data.
- Evaluate the feasibility of **post-clearcutting monitoring** (over a time lag of about ten years), on a national or regional scale, based on aerial or satellite imagery, to document the transformation of stands (e.g. from broadleaved to conifers).

Environmental impacts of clearcutting

Physio-chemical effects

- Fine-tune the **national mapping of fertility loss risks** subsequent to nutrient exports (participative research underway).
- Develop **dynamic maps** of risks to the **physical integrity of soils** (water erosion, compaction) taking into account changes in plant cover and weather conditions.
- Develop **multi-criteria analysis** tools (e.g. For-Eval[18]) to assess the degree of vulnerability of plots to clearcutting or its mechanised operations.
- Check whether the **effects of heavy machinery on soil compaction** observed in the forest areas of Compiègne and Amance over the past few decades based on plant communities, can be found also on a national scale (mobilisation of national biodiversity databases, including IFN database).

Biodiversity

- Set up local **monitoring** or **observational studies** and/or **dedicated experiments** to evaluate several taxonomic groups in the short, medium and long term in the context of French temperate forests:
    1) Effects of **clearcutting** and shelterwood cutting on biodiversity, including the feeding behaviour of wild ungulates.
    2) Effects of **retention**, keeping **brushwood** and **stumps** in place, not only in the case of clearcutting but also for shelterwood regeneration cuts and selection cuts in the broad sense.
    3) Effect of **planting** compared to natural regeneration after regeneration felling, whether with regular or irregular (gap planting) treatment.
    4) Effect of a wide gradient of **clearcut sizes** under different biogeographical conditions.
- Conduct **experimental research** in a French temperate context to assess the effects of **mechanised soil preparation** during planting on biogeochemical functioning and soil biodiversity, and compare with the effects of alternative measures (localised tillage) on these two aspects and on plantation success.
- Design and implement studies to assess the effect of the **unit area, quantity** and **spatial arrangement of clearcuts** in the landscape on biodiversity, and compare with other types of felling, particularly irregular treatments.
- Centralise data on the **linkage between tree species and associated diversity**, via a database of faunistic species associated with tree species, and supplement it with studies on this linkage in order to document the effects of planting with species switches and assess the cascading impacts of declines in forest species or increases in other species.
- Identify **thresholds for the proportion of introduced tree species** causing negative impacts by modelling biodiversity in relation to tree species at landscape scale.
- Intensify the research into **cascade effects** and interactions between regeneration cuts, their spatial and temporal arrangement, **plant species** and **large wild ungulates** .
- Develop knowledge on **retention practices** to promote biodiversity, the microclimate and the colonisation of seedlings by ectomycorrhizae: pruning and distribution of trees or clumps to prevent their decline in open environments (post-felling) and in drought or heatwave conditions, and secure the expected effects.

Humanities, Social Sciences and Economics

- Design a **research observatory** on public mobilisation and conflicts in the forest.

[18] Available here: https://www.onf.fr/onf/+/7e7::application-mobile-for-eval.html

- Map and characterise the **level of public mobilisation in forests** with regard to clearcutting and renewal methods in **other European countries** by means of a collective research project at European level (e.g. COST project).
- Monitor and evaluate the **social effects of felling restrictions** in areas where experiments of this type have been carried out.
- Analyse the **determinants of the perception of different types of felling** (clearcutting, natural regeneration, variable surface area, etc.) and **reforestation** by various groups of stakeholders (forest owners and managers, and users) and in different forest contexts in mainland France.
- Analyse the **sociological characteristics of activist groups involved** in the protests (recruitment, age, socio-demographic profile) and their reasons for joining (networking methods, spatial scale).
- Analyse the **capacity of public protests to modify or not the practices** in the field, as well as the reference systems (voluntary, normative, regulatory).
- Build **biophysical and socio-economic databases** on ecosystem services at relevant spatial and temporal scales.
- Generalise **cost analyses of felling worksites** in relation to their size, nature and the stands concerned.
- Encourage the development of **growth models** applicable to uneven-aged stands or stands of any structure.
- Promote the search for **multifunctional trade-offs** between ecosystem goods and services.

Forest stand renewal

Natural regeneration

- Set up a **permanent system for monitoring natural regeneration** to determine its dynamics and success rate (a system is currently being deployed by the IGN).
- Analyse the **factors hindering natural regeneration** and identify silvicultural levers to control these factors and mitigate their impacts.
- Revisit past research on the effects of retaining a **mature shelter**, **lateral shelter** or **regrowth** on young natural regenerations and plantations.

Plantations

- Design cultivation methods to reduce **transplant shock** and improve plant regrowth in summer drought conditions.
- Using the **"targeted seedlings" concept**, identify the characteristics of the seedlings best suited to each planting environment, and produce seedling types with diversified characteristics to be directed to the planting environment where they will perform best.
- Design innovative sequencing protocols for the **management of seed orchards** and **selected forest stands**, adapted to future climate and health conditions, in order to increase seed production capacity.
- Improve knowledge on the **performance of "new species"** in order to define the species that will best respond to future constraints, and prioritise breeding efforts towards these species.

Pests and Ungulates

- Study the life cycle and mode of action of **bioaggressors in natural regenerations and plantations**, in order to design control methods.
- Develop **tools for early detection** and **reporting of bioaggressors**, as well as cultivation methods to mitigate the damage they cause.

- Study the effects of the **forest mosaic** on the **behaviour of ungulates** in order to improve territorial strategies of ungulate population control.
- Gain a better understanding of the **interactions between ungulates, forest renewal and plant communities** in order to develop operational tools for assessing accurately the intensity of impacts by ungulates on forest renewal.
- Determine a **tolerable browsing threshold**, beyond which the impacts on the stem quality in a regenerating stand would cause significant losses.

Regeneration post disturbances

- Analyse the **dynamics of post-disturbance renewal** using a gradient of increasing intervention, from planting to free evolution.
- Set up **post-disturbance observatories** and maintain existing observatories to study disturbances and define integrated management methods for these disturbances.

Establishment of mixed stands

- Characterise the **behaviour of mixed species** at the younger stages, in a wide variety of contexts.
- Document the **development dynamics** and the **technical and economic assessment of existing mixes in early stages**, select operational mixes and promote their extension in ad hoc contexts.
- Using **mixed-stand growth models**, explore a wide range of scenarios and field-test the most promising combinations.

Cross-cutting issues

- Analyse the **impact of mechanised operations** (logging, slash management, mechanised site preparation, partition maintenance, silvicultural work) on the **physical, chemical and biological properties of the soil**, according to the operational conditions.
- Design **high-performance planting protocols** (technical, economic, environmental and social performance).
- Develop **multi-criteria evaluation models** to identify plantation management modus operandi that offer the best compromise between technical and economic success, preserving the ecological integrity of ecosystems, and accommodating the recreational activities of urban and rural populations.

Avenues for improvement in forestry management and the forest/wood industry

This section sets out a number of possible improvements that will enable stakeholders in forestry management and the forest & timber industry to mitigate the negative effects of clearcutting and improve performance in forest stand renewal in the context of a necessary adaptation to climate change.

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Environmental impacts of clearcutting

Physio-chemical effects

- **Avoid clearcutting where its impact on the physical environment is greatest**; this is particularly the case when clearcutting takes place at distances of less than 30 m (and sometimes even more), on fine-textured soils or on sloping land.

- Elsewhere, the **negative effects** of clearcutting can be **greatly mitigated** by leaving slash in place (foliage, of course, but also some of the branches and stumps), by hauling the timber logs according to the rules (on dry ground, respecting pre-defined partitions, using machinery suited to the type of soil, etc.), and by limiting the size of cutovers and the amount of tillage. Comprehensive **guides** and **digital applications** (e.g. For-Eval) already exist to help managers apply these levers in their practices to mitigate the impacts of clearcutting, depending on the situation.
- Boost up initial and continuing **training programmes** in the use of these guides and digital applications.

Biodiversity

- Combine, as much as possible, **complementary measures** at **landscape** and **plot levels**:
  1) **At plot level**: Implement **practices to retain** biodiversity supports (tree habitats, slash, woody regrowth) and preserve the soil, already identified in best practices guides[19] and certification standards (PEFC and FSC). Regarding **renewal methods**, where silvicultural constraints and the future climate allow, opt preferentially for natural regeneration over planting, native rather than exotic species, and mixed rather than pure plantations. If replanting is chosen, it is preferable to replant quickly (unless contraindicated, for instance in case of Hylobius weevil or if a natural regrowth is preferred as a beneficial auxiliary), and to retain woody species in the undergrowth when felling (to facilitate root colonisation of the seedlings by ectomycorrhizae).
  2) At **landscape scale**: Modify the proportions of even-aged, uneven-aged and free-growing stands in the forest mosaic, by increasing the current proportion of **uneven-aged high forest** - without however generalising it -, reinforcing the network of **free-growing reserves**, and limiting clearcutting **near reserve areas**. Such measures would make it possible to mitigate the lasting negative effects of regeneration cuts in even-aged high forest on **specialist forest species** in mature stands that have no alternative habitat other than the forest, while preserving the positive effects of clearcuts on declining open-habitat species.
- Revisit the above-mentioned biodiversity options, taking into account their **technical feasibility**, their **effectiveness** in the biogeographical contexts of mainland France[20], and the findings on the other issues examined in the assessment (see in particular the cross-cutting issue on: “Preserving forest ecosystems in a context of mechanised silviculture”).
- Preserve buffer strips of at least 30 metres along the edge of watercourses, wetlands and freely evolving protected areas.

Humanities, Social Sciences and Economics

- Establish a **diagnosis** of the landscape, ecology, heritage and recreational uses of the plot or group of plots to be felled.
- Adapt the **size of felling** according to this diagnosis and the locally acceptable thresholds or the thresholds mentioned in PEFC or FSC-type standards.
- Ensure that felling sites and access roads are **restored** to their original condition after completion of the felling work.

[19] See Gosselin & Paillet, 2017, *Guide Pratic'sols*, and ADEME Guide “*Récolte durable de bois pour la production de plaquettes forestières*” (Sustainable timber harvesting for the production of forest fuelwood chips).

[20] These avenues are based on the scientific literature, which is dominated by research on boreal forests and temperate forests in North America. The mechanisms on which they rely can probably be transposed to the temperate forests of mainland France.

Forest stand renewal

- Develop natural regeneration management protocols that ensure the arrival of new seedlings as long as regeneration is not effectively established (i) by seizing **natural regeneration opportunities** during favourable fruiting years, monitoring the quality of fruiting, and initiating regeneration cuttings as soon as the opportunity arises, and (ii) by **retaining seed trees in the plots** as long as a sufficient regeneration capital (number of seedlings regarded as effective) is not present.
- In the hottest and driest conditions, retain a **mature canopy** above the regeneration plot to encourage the establishment and development of seedlings, adapting its density to the temperament of the species.
- In plantations, special attention must be afforded to the **logistical supply chain** from the time **the seedlings leave the nursery** to the time they are **planted** in the plots. This must be done in such a way as to protect the seedlings as much as possible from the stresses to which they may be subjected, in order to ensure their regrowth ability, even in adverse climate conditions.

Main avenues for public action

This section compiles some potential avenues for public policy players.

Clearcuts monitoring

- Support the development and implementation of a **high-performance, transparent tool for monitoring changes in canopy** (clearcutting, other types of felling, damage due to various hazards) in conjunction with the IGN's Forest and Wood Observatory and the Theia scientific cluster, and introduce a **shared diagnostic assessment** into the PRFB programmes (*Programme Régional de la forêt et du bois*).

Environmental impacts of clearcutting

- Develop an **active policy to protect forest soils** (implementation of the national soil conservation plan), in particular to speed up the **development of logging cableways in lowland** areas.
- Reinforce the **training of forestry contractors** in virtuous forest-friendly practices.
- Increase the resources allocated to research in the field of forest biodiversity, in particular on the influence of various **forest management methods** on biodiversity, including certain practices such as windrowing or retention of isolated trees or clumps.

Social issues, Regulations and Economics

- Support the establishment of a **media observatory** for conflicts and controversies on forests, in conjunction with the Forest Observatory set up by the IGN.
- Consolidate the **discussion and decision-making arenas** (local, regional, national) to encourage the emergence of new capacities for social and symmetrical learning on the part of the various protagonists in forestry conflicts.
- Address the issue of clearcutting and, more generally, forestry policy at the **regional scale** (forestry charters, Regional Nature Parks, etc.**)**.
- Support **experiments** in innovative and collaborative forestry management protocols in pilot areas (inside and outside protected areas).
- Increase the resources allocated to research in the field of **economic** and **legal sciences**.

Further assess the added value of **legislating** the size of clear-cutting based on the ecological, technical, economic and social knowledge acquired in the CRREF expertise.

Forest stand renewal

- Mobilise the funding needed to set up **new seed orchards**.
- Support experimental networks for benchmarking **new species and provenances** (ESPERENCE network).
- Promote a harmonised **monitoring system**, accessible to the stakeholders of plantations created as part of the **France Relance** and **France 2030** national recovery plans, as a support to adaptive management.
- Organise **feedback of experience** in renewals of **plots under management**, to leverage the lessons learned from innovative technical solutions implemented by forest managers, and analyse the performance of these management protocols along broad biogeographical gradients.
- Bolster **consultation between forest managers and seed and seedling producers** to better define the needs by species and the production possibilities in the short and medium term (3 to 20 years).
- Encourage the development of **cultivation contracts** to provide visibility on the forest managers' short-term expectations.

Acronyms and abbreviations

ADEME: Agence de l’environnement et de la maîtrise de l’énergie (French Environment & Energy Management Agency)

AFB: Alliance Forêts Bois

CBPS: Code des Bonnes Pratiques Sylvicoles (Code of Good Forestry Practices)

CIBE: Comité interprofessionnel du bois énergie (Inter-Professional Fuelwood Committee)

CNES: Centre national d'études spatiales (National Centre of Spatial Studies)

CNPF: Centre national de la propriété forestière (National Centre of Forest Property)CNPF-IDF: Institut pour le développement forestier (Institute for Forestry Development)

COPACEL: Union française des industries des cartons, papiers et celluloses (French Union of Board, Paper & Cellulose Industries)

CRREF: Coupes Rases et REnouvellement de peuplements Forestiers (Clearcuts and REnewal of Forest Stands)

CSF Bois: Comité Stratégique de Filière Bois (Strategic Wood Industry Committee)

DDT: Direction départementale des territoires (Departmental Directorate for Territories)

DGD: Documents de gestion durable (Sustainable Management Documents)

DRAAF: Direction régionale de l’Alimentation, de l’Agriculture et de la Forêt (Regional Directorate for Food, Agriculture and Forestry)

DREAL: Direction régionale de l'Environnement, de l'Aménagement et du Logement (Regional Directorate for the Environment, Land Planning and Housing)

DSF: Département de la santé des forêts (Forest Health Department)

EFF: Experts Forestiers de France

FBF: France Bois Forêt

FBIE: France Bois Industries Entreprises

FCBA: Institut technologique Forêt Cellulose Bois-Construction Ameublement (Technology Institute Forest, Cellulose, Lumber, Furniture)

FFN: Fonds forestier national (National Forestry Fund)

FNB: Fédération nationale du bois (National Timber Federation)

FNC: Fédération nationale des chasseurs (National Federation of Hunters)

FNCOFOR: Fédération nationale des communes forestières (National Federation of Forest Communities)

FNE: France Nature Environnement

FNEDT: Fédération nationale des entrepreneurs des territoires (National Federation of Territorial Entrepreneurs)

FSC: Forest Stewardship Council

GRECO: Grande région écologique (Large ecological region)

SER: Sylvoecoregion

IEFC: Institut Européen de la Forêt Cultivée (European Institute of Planted Forests)

IFN: Inventaire forestier national (National Forest Inventory)

IGN: Institut national de l'information géographique et forestière (National Institute for Geographic and Forestry Information)

INRAE: Institut national de la recherche pour l’agriculture, l’alimentation et l’environnement (National Research Institute for Agriculture, Food & Environment)

MASA: Ministère de l’Agriculture et de la Souveraineté alimentaire (Ministry of Agriculture and Food Sovereignty)

M€: million euros

Mha: million hectares

MTECT: Ministère de la Transition écologique et de la Cohésion des territoires (Ministry of Ecological Transition & Territorial Cohesion)

OFB: Office français de la biodiversité (French Biodiversity Office)

ONF: Office national des forêts (National Forests Office)

ONG: Non-Governmental Organisation

PEFC: Programme for the Endorsement of Forest Certification

PNFB: Programme national de la forêt et du bois (National Forest & Timber Program)

PNR: Parc naturel régional (Regional Nature Park)

PRFB: Programme régional de la forêt et du bois (Regional Forest & Timber Program)

PSG: Plan simple de gestion (Simple Management Plan)

RNF: Réserves naturelles de France

RTG: Règlement type de gestion (Standard Management Regulations)

SFCDC: Société forestière de la Caisse des Dépôts et de Consignation

SRGS: Schéma régional de gestion sylvicole (Regional Forestry Management Plan)

UCFF: Union de la coopération forestière française (Union of French Forestry Cooperation)

IUCN: International Union for Conservation of Nature

WWF: World Wildlife Fund

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We wish to thank the following reviewers of one or several contributions:

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We also wish to thank seven other anonymous reviewers.