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Nathalie Korboulewsky, Isabelle Bilger. PSDR DEFIFORBOIS -Development and sustainability of the forestry and timber sector in the Centre-Val de Loire region. Innovations Agronomiques, 2024, 86, pp.53-68. 10.17180/ciag-2024-vol86-art05-GB . hal-04702078

HAL Id: hal-04702078
https://hal.inrae.fr/hal-04702078v1

Submitted on 19 Sep 2024

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PSDR DEFIFORBOIS - Development and sustainability of the forestry and timber sector in the Centre-Val de Loire region

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Ensuring sustainable forest management while strengthening the competitiveness of the forest and wood-products sector is a major challenge for the economic development of rural areas in the Center-Val de Loire region. Upstream actors in the sector face two challenges: first, harvesting more wood to meet the increasing demand for wood products and renewable energy without deteriorating the already poor soils predominant in the region's forests; and second, finding solutions to help forests adapt to climate change. In the PSDR DEFIFORBOIS project, researchers and actors from INRAE, ONF, FCBA, Fibois, CNPF and Unisylva have joined forces to carry out: i) a prospective analysis of the means required to ensure an increased harvest of forest resources for regional logging companies'; ii) a technical and environmental diagnosis of local whole-tree harvesting practices and their impact on soils and biodiversity so as to propose recommendations for sustainable fuelwood harvesting methods adapted to the regional context.

Keywords: fuelwood, Whole-tree harvesting, Soil fertility, Climate change, Adaptation, Tree species.

Introduction

With a target of carbon neutrality by 2050, France is committed to a low-carbon strategy and the development of renewable energies, in which forests and wood resources play a major role. However, the forestry and wood-based industries are facing two challenges: firstly, meeting the growing demand for wood, and a diversification of its uses; and secondly, responding to climate change, which poses a serious threat to forests in the 2050 timeframe (Roux et al. 2020). Although the predicitons in climate and societal models are somewhat uncertain, the current context is imposing far-reaching changes in both forestry practices and the socio-economic environment (Thiffault et al., 2016; Hansen et al., 2017; IIASA, 2017).

Most of the forests in the Centre-Val de Loire region are privately owned, and although they contain significant timber resources, they are under-exploited: the wood harvested accounts for less than half of the annual growth in these forests. According to a national study on wood availability, stepping up forest management would enable substantial gains in production - more than 2 million m^3/year by 2036 - under a more dynamic management scenario (IGN data, Simon and Colin, 2018). However, the changes required to achieve this objective raise questions, particularly concerning the investments required for harvesting companies, the impact additional harvests and new harvesting practices would have on the soil and on biodiversity, and how to adapt or transform forest stands in the face of future climatic conditions (Legay et al. 2019). Led by INRAE between 2016 and 2020 in partnership with regional actors, the PSDR DEFIFORBOIS project called "Development and sustainability of the forest and wood industry in the Centre-Val de Loire region" is providing some answers.

To increase timber harvesting by 31% between 2016 and 2026, an objective set out in the Regional Forest and Wood Plan, an increase in the rate of mechanised harvesting will be required. To determine the proportion of the harvest that could be mechanised by 2026 and to assess the resources needed to achieve this, the FCBA carried out a prospective study as part of the DEFIFORBOIS project.

Over the last ten years, the use of wood chips to fuel biomass heating systems has grown considerably in the Centre-Val de Loire region. These chips come mostly from hardwood stands that are often poor or in decline, and are generally produced by grinding whole trees. This type of mechanised harvesting exports far more mineral elements from the stand than does conventional harvesting by drastically reducing the stock of dead wood left after felling. This leads to the risk of reducing soil fertility over time (Achat et al., 2015a; 2015b; 2018, Ouimet et al. 2021) and eliminating habitats favourable to biodiversity. To limit these risks, the DEFIFORBOIS project sought to determine where and how to harvest woody biomass in the Centre-Val de Loire region, while still preserving soil fertility and biodiversity.

First, INRAE carried out an analysis of the sensitivity of the region's soils to biomass exports, based on data from the literature and the IGN Forest Inventory, and the FCBA and Fibois CVL identified the most common methods of harvesting woody biomass in the region. Next, INRAE led an *in situ* study focused on nine woody biomass harvesting sites set up by ONF Energie and Unisylva in four sectors (Orléanais, Sologne, Perche and Touraine, Figure 1A). These sites were subjected to in-depth analysis based on pre- and post-harvest field surveys (soil, stand, flora, deadwood), statistical modelling to calculate biomass (Deleuze et al., 2014), and physico-chemical laboratory analyses. We also combined and used the database on forest soils, containing both pedological information (e.g. texture) and chemical analysis, from different sources (CoopEco, Ecoplant, GISCOOP, Donesol, Renecofor) adding some additional data provided by GisCoop, the chamber of agriculture of Indre (Regional Pedological Reference) and EUROSTAT (LUCAS database) (651 soil profiles, Figure 1B). Finally, we established a map of soil sensitivity-to-harvest based on 1/250 000 scale maps of the Regional Pedological Reference produced by the county Chamber of Agriculture (Richer de Forges A. et al, 2014) and INRAE Infosol (maps for 4 ou t of the 6 counties in the region were available: Cher, Indre, Indre et Loir and Loiret).

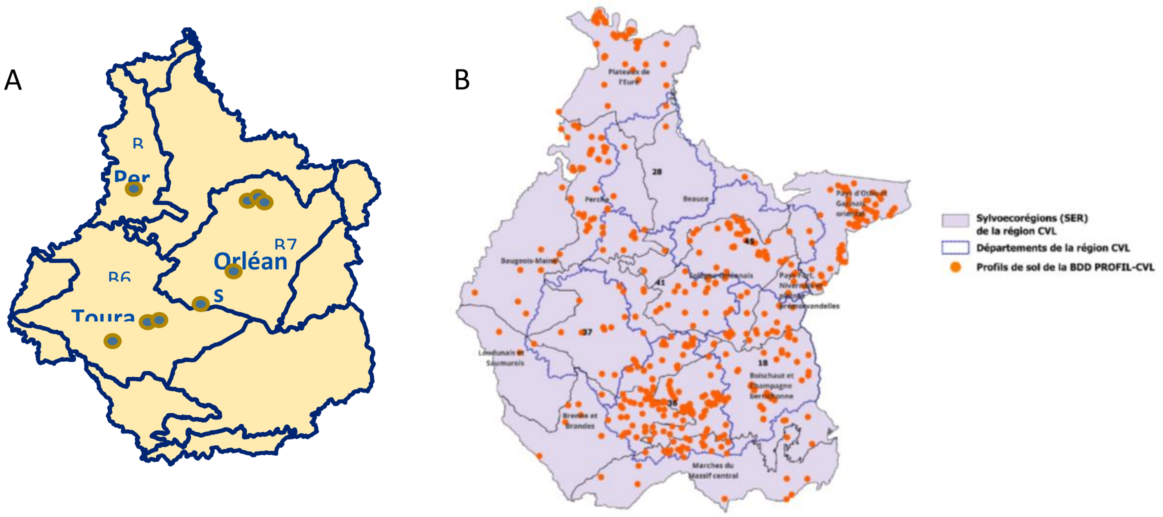


Figure 1: Location of A) the nine biomass harvesting sites studied in four forested areas in the Centre-Val de Loire region, and B) of the 651 soil profiles combined in the database used.

1. Main results

<u>1.1 Increased production of woody biomass, harvesting practices and environmental impacts</u>

1.1.1 Additional production is conditional on investment in machinery and labour

The inventory of the current forestry machinery fleet (harvesters, chippers) in the Centre-Val de Loire region reveals that woody biomass harvesting has increased signifcantly (Cacot et al., 2016).

In addition, the prospective analysis of the potential development for forest harvesting in the Centre-Val de Loire region (Boldrini and Cacot, 2016) indicates that an additional 33% of woody resources can be made available to mechanised harvesting by 2026, according to a scenario based on the expected natural increase in the resource (+ 0.5 million m^3 per year). This additional resource could reach as much as 61% according to a more intensive scenario in line with the objectives of the National Forestry Plan (Plan National Forêt Bois, , +1.1 million m^3 per year). However, overall labour capacity in the logging sector is expected to fall by 42% compared with 2016, whereas an additional 71 to 147 felling and skidding machines and 78 to 157 jobs will be required, depending on the scenario (Cacot *et al.,* 2016). These results, along with recommendations for staff training and equipment acquisition to support companies' development, were presented to the Regional Forestry and Timber Commission, and then adopted by the regional authorities to define the operational objectives included in the Regional Forestry and Timber Plan.

1.1.2 Woody biomass is mainly harvested from whole trees in hardwood stands

The 2015 survey of harvesting practices for the production of wood chips in the Centre-Val de Loire region reveals that most of the material comes from small hardwoods (coppice or undergrowth) harvested as whole trees. Harvesting generally occurs during the growing season (April to September) so as to take place outside hunting season and to avoid periods when the soil is waterlogged. These cuts, which are designed to improve or regenerate stands, are highly influenced by weather factors, which have an impact on soil bearing conditions (waterlogged soils), by the demand for woody biomass from industrial heating plants, by the state of existing stocks, by quality requirements for the wood chips, and, in some of the region's private forests, by hunting management plans.

1.1.3 Forest soils are sensitive in most of the region

An analysis of data collected by the National Forest Institute (NFI) on 4,393 forest plots in the region (Korboulewsky and Bilger, 2018) shows that the region's forest soils are sensitive to chemical fertility loss. Half of the soils are acidic, with a pH below 5.2; more than 40% of the surface soils (0-10 cm) are sandy or sandy-loam; and a more than half are hydromorphic (Pseudogleys with temporary waterlogging).

This means that most of the forest stands in the region have soils that are sensitive to physical damage (56% of the plots), and that they are also sensitive to loss of fertility (55% of the plots). Therefore, soil compaction will easily occur if heavy machinery is used in unappropiate conditions, and soil fertility will decline in case of intensive or too frequent harvesting. There are disparities between the different sylvoecoregions (SER), however. In the Sologne-Orléanais (SER B70) and Beaugeois-Maine (B61) ecoregions, respectively 66% and 69% of the plots are highly sensitive to fertility loss, whereas this is the case for only 24% and 12% of the plots in the Champeigne-Gâtine tourangelle (SER B62) and in the Boichaut and Champagne berrichonne (SER 91) ecoregions, respectively. The initial regional map of soil sensitivity to increased biomass harvesting, which resulted from this work, was used as a basis for discussions with project stakeholders.

The soil sensitivity in the region's studied forest plots was confirmed by chemical analyses, based on sensitivity thresholds from the "Insensé" project (Augusto *et al.*, 2018; Durante *et al.,* 2019), of around twenty samples and around fifty other data from the Loiret Regional Soil Reference Guide (Référentiel Régional Pédologique du Loiret, RRP45; Richer de Forges, 2008) and the forest-site types catalogue for Orléans (Brêthes, 1993). This sensitivity is due to low concentrations of N, K, Mg and P, given that more than 60% of the forest sites in the dataset are highly sensitive to at least three of these elements.

The study also shows that soil texture in the 0-10 cm layer alone could be a good predictor of sensitivity to chemical fertility loss in this region. Three soil texture classes were therefore defined (Table 1):

– Predominantly sandy soils (S sandy soils, SL sandy-loam soils): These soils are very sensitive, as the export of nutrients from a single whole-tree harvest can easily exceed the stock of nutrients in the top 10 cm of soil. Furthermore, replenishing the nutrient stock in these soils takes a long time so exporting biomass from these stands will have a detrimental effect on soil fertility in the long term. We strongly advise against harvesting whole trees on this type of soil.

- Predominantly clay soils (A clay soils, AL silty-clay soils, ALO heavy clay soils): these soils are the least sensitive because they store more nutrients than other types of soil.
- All the other soils, with predominantly silty or balanced textures (AS, SA, LSA, LAS, LA, LS, LSM, LM, LLS, LL) may range from highly to moderately sensitive; only chemical analyses would enable foresters to make informed, reliable decisions in these cases. In addition, silty soils are the most sensitive to physical damage such as compaction and rutting.

Table 1: Sensitivity of Centre Val de Loire region soils to whole-tree harvest according to the textural class (Aisne triangle of 15 classes). The sensitivity note is the average of the sensitivity for the 5 elements (N, P, K, Ca, Mg).

Texture	Textural class*	Sensitiviy note	Sensitivity level
Clayish	A, ALO, AL	<0.25	low
Mixed, contain clay	AS, LA, LAS, LSA	0.25 - 0.4	medium
Mixed, mainly silty or sandy	LM, SA, LMS, LLS	0.6 – 0.75	medium
Sandy	S, SL, LS	>0.75	high

*A: clay; S: sand; L: loam

The work on soil sensitivity allowed us to produce sensitivity maps at the regional (Figures 2 & 3) and county (Figures 4 and 5) levels. The regional maps are based on soil descriptions from the National Frest Inventory, and the map (1/250 000e) of the Pedological Regional Reference (Richer de Forges A. et al, 2014) while the county maps are based on the Loiret soil map and enable a more detailed representation (maps including the percentages of moderately and highly sensitive soils were also produced). A large majoriy of soils in the region have a medium (41%) or high sensitivity (48%) (Table 2). Nevertheless, even in the same departemental county, there are great local differences. For instance, in the Loiret, South of the Loire River, in Sologne, more than 80% of the soils are highly sensitive (the remaining 20% are moderately sensitive; none were insensitive). In contrast, to the North, in the Orléans forest, a significant proportion (more than 20%) of the soils are not very sensitive (Figures 4 & 5).

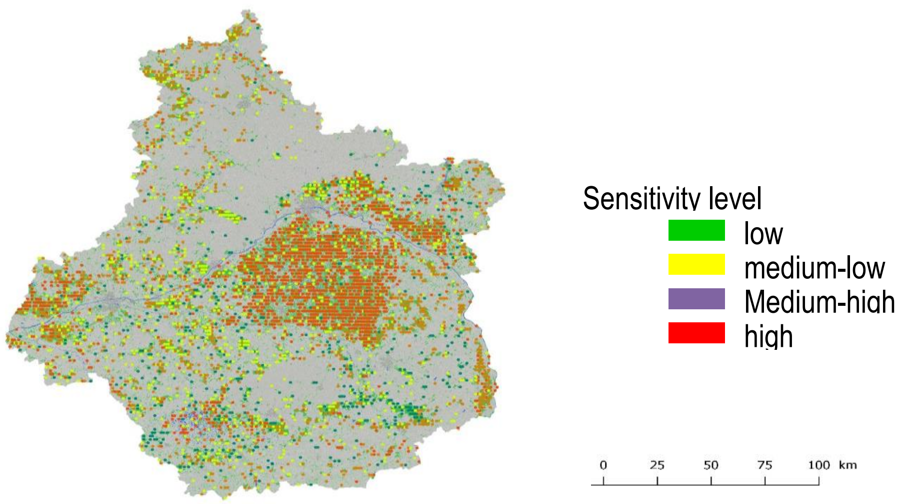


Figure 2: Soil sensitivity to biomass export based on soil texture at a depth of 0-10 cm recorded by the National Forest Inventory (IFN) at forest plots in the Centre-Val de Loire region, ranging from low (green) to high (red) for the least sensitive to the most sensitive soils.

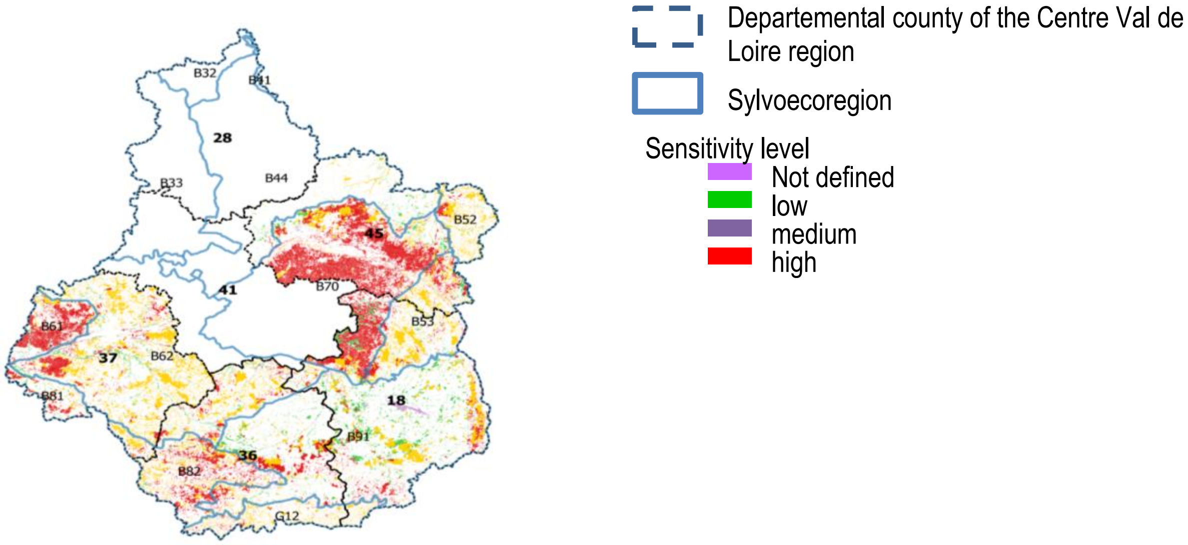


Figure 3: Soil sensitivity of forested area to biomass export based on the maps (1/250 000e) of the Pedological Regional Reference (Richer de Forges A. et al, 2014) in the Centre-Val de Loire region (except for county 41 and 28), ranging from low (green) to high (red) for the least sensitive to the most sensitive soils.

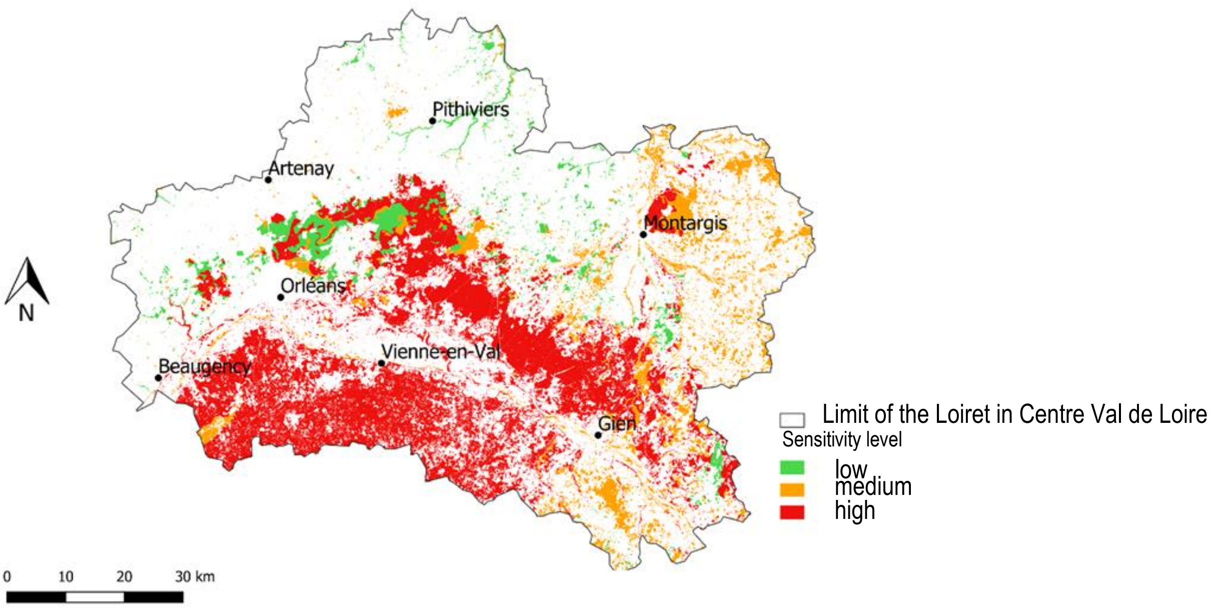


Figure 4: Soil sensitivity to biomass export in the Loiret based on BD Forêt V2 data (IGN) (Richer de Forges et. Lehmann, 2008). Forested areas with a majority of soils in the high sensitivity class are shown in red, those in the medium sensitivity class in orange, and those in the low sensitivity class in green.

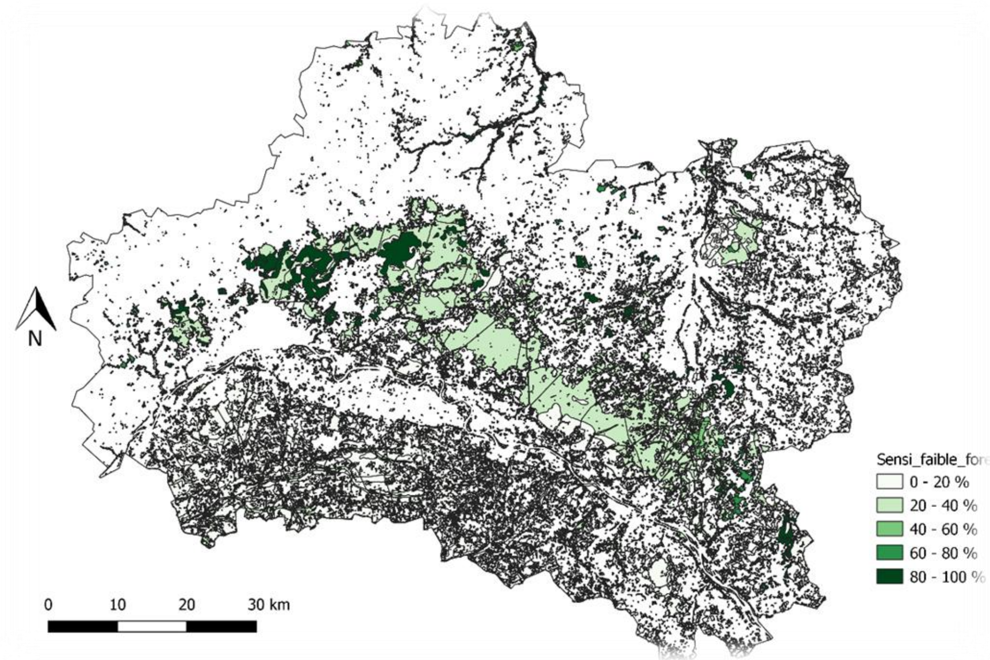


Figure 5: Map showing the percentage in surface area of each Loiret Soil Map Unit (UCS 45) for forests with low sensitivity based on the texture and mineral richness of the surface stratum (0-10 cm) of the Soil Typology Units (UTS), from BD Forêt V2 data (IGN) (Richer de Forges and Lehmann, 2008).

Table 2: Distribution of forest areas by sensitivity level in each departmental county

	Cher (18)	Indre (36)	Indre-et-Loire (37)	Loiret (45)	Department 18-36-37-45
% forested area	26%	20%	24%	30%	100%
Sensitivity level					
low	21%	10%	7%	5%	11%
medium or undefined	40%	47%	54%	27%	41%
high	39%	43%	39%	68%	48%

1.1.4 Sites vary widely in terms of the diameters cut and the volumes removed

The sites selected are representative of the stands (and the soil types) where whole-tree felling is practiced in the Centre Val de Loire region. Of the nine sites studied, two were clearcuts to be replanted and seven were partial cuts for improvement, sanitation or removal of the understory to encourage natural regeneration (canopy survey) (Table 3). Harvested species varied according to region and silvicultural treatment, but most of the work sites were in mixed stands consisting mainly of hornbeam, chestnut, birch, aspen and oak. Three sites were located on highly sensitive soils, five on moderately sensitive soils and one on slightly sensitive soil.

Table 3: Dendrometric characteristics of the sites studied

Site	Stand type	Type of felling	Main tree species harvested*	Standing basal area before cut	Basal area harvested (before minus after)	Felling intensity (% BA cut)	Mean quadratic diameter harvested (cm)
B7	Mix of high forest and coppice, low-reserve	Improvement: coppice cutting, balivage	chestnut, oak, birch	23	12	50%	5
B9	Mix of high forest and coppice, low-reserve	Improvement: coppice cutting, balivage	aspen, oak	33	25	76%	9
Ch	High forest from conversion	Understory cut before regeration cut	aspen hornbeam oak	36	23	65%	13
Co	High forest from conversion	Understory cut before regeration cut	hornbeam	46	11	23%	13
LaV	Mix of high forest and coppice	Understory cut before regeration cut	chestnut, black locust	33	19	57%	7
Pru	Coppice	Coppice cutting	chestnut	52	43	82%	12
Se	Mix of high forest and coppice	Clean cut	aspen, hawthorn, wild cherry	29	29	100%	7
StV	Mix of high forest and coppice	Coppice cutting	chestnut, birch	32	29	88%	8
Su	High forest from conversion	Understory cut before regeration cut	aspen	44	22	50%	12

(*) Species representing more than 10% of the total basal area harvested

Comparing the dendrometric surveys before and after felling and estimating the amount of biomass removed from the site reveal clear differences in harvesting intensity and diameter of the trees removed, even for similar types of felling (Table 3). Basal area before felling ranged from 23 to 52 m²/ha, and after felling from 0 to 35 m²/ha, with a felling intensity ranging from 23 to 100%. Total biomass removed varied from 38 t/ha for a understory cut to 186 t/ha for a clear cut in a dense coppice. Although the average diameter of the stems cut varied from 5 to 13 cm, above all, the distribution of the different diameter classes in the total biomass cut was very different. Small-diameter (<7 cm) stems accounted for 2 to 31% of the biomass removed, depending on the site. However, when small wood from the crowns of larger trees is added to the small-diameter stems, this represents on average 1/3 of the total biomass cut (Figure 6). It is the small wood and fine branches of the tree that are the richest in mineral elements (André, 2010; 2003). Therefore, both the volume and the size of the woody biomass removed have an impact on the quantity of minerals exported and should be taken into account when assessing the risk of fertility loss from whole-tree removal.

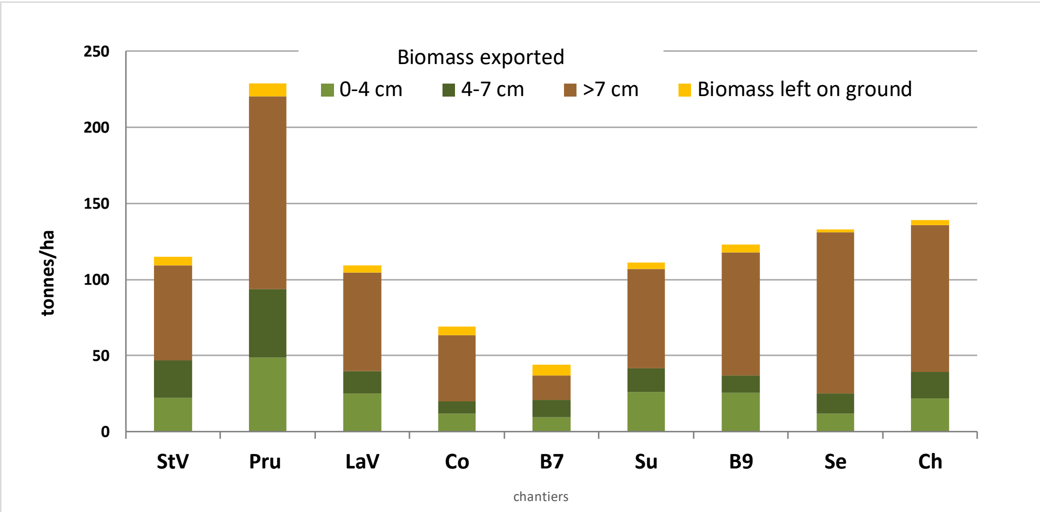


Figure 6: Woody biomass removed from each site according to diameter.

1.1.5 Few cutting residues are left on the ground

Our measurements show that more than 90% of the total biomass cut is removed from the plot (Figure 6). The quantity of wood left on the ground after felling and skidding operations – called felling residues or brashbrash (British term) - is calculated as the difference between the quantity of wood on the ground before and after silvicultural operations. In pre- and post-harvest surveys, we estimated the volume of downed woody debris with the Line Intersept Sampling method (Marshall et al., 2000), then translated this amount into biomass (based on the density of wood samples measured in the field). This work led to a new methodology and the publication of a reference field protocol (Korbouleswky et al., 2021).

When different diameter classes are considered, we find that the larger the diameter of the wood, the less is left on the ground. On average, 7% of small wood remenants (Ø < 7 cm) in biomass are left on the ground (11% for 0-4 cm and 3% for the 4-7 cm); the figure drops to only 2% for large wood (Ø > 7 cm) (Bessaad et al., 2021a). However, national guidelines recommend leaving at least 10% of the cut small wood on site; 30% in the case of moderately sensitive soils (Ademe, 2020). Furthermore, in terms of floral biodiversity (Miton, 2019), our pre- and post-harvest surveys show that whole-tree removal has strong short-term effects on species richness. First, it favours heliophilous wetland species and bryophyte species growing on small-diameter downed deadwood (< 4 cm in diameter) with an increase of more than

10% in the total number of these species after felling. On the other hand, whole-tree removal disadvantages forest, wetland and saprolignicolous bryophyte species with a loss of more than 10% in the number of species after felling. In addition, for some sites, our study reveals that some of the pre-existing medium- (4-7 cm) and large-diameter (>7 cm) lying deadwood was removed from the site during harvesting operation. According to the general PEFC guidelines, all pre-existing lying woody debris, as well as a few logs from the felling, should be left on the ground as refuges for biodiversity.

In addition, the length of time that piles of felled timber are left to dry out before skidding (on average, one and a half months according to our study) is not sufficient for the leaves to fall off naturally, while handling and skidding leaves very little residue on the ground. The national recommendations (Ademe 2020) stipulate that felling in winter (when leaves are not present) should take precedence, and if this is not possible, felled trees should be left to dry out in the plot for several months so that as many leaves as possible fall to the ground to guarantee sufficient nutrient returns via leaching by rain (Bessaad et al., 2020). For oak, the optimum period appears to be six months (Bessaad, 2020). By decomposing, leaves and wood return nutrients and organic matter to the soil, and these are essential for maintaining soil fertility.

1.1.6 Nutrient export is doubled when whole trees are harvested

The analysis of the N, K, Mg, Ca and P concentrations of more than 600 wood and leaf samples taken from the study sites confirms that small wood is 2 to 3 times richer in nutrients than large wood, while leaves are up to 7 times richer (Figure 7). On the Centre Val de Loire sites, the removal of small pieces of wood resulted in the export of almost twice as many nutrients as would have been the case if only large pieces of wood had been harvested.

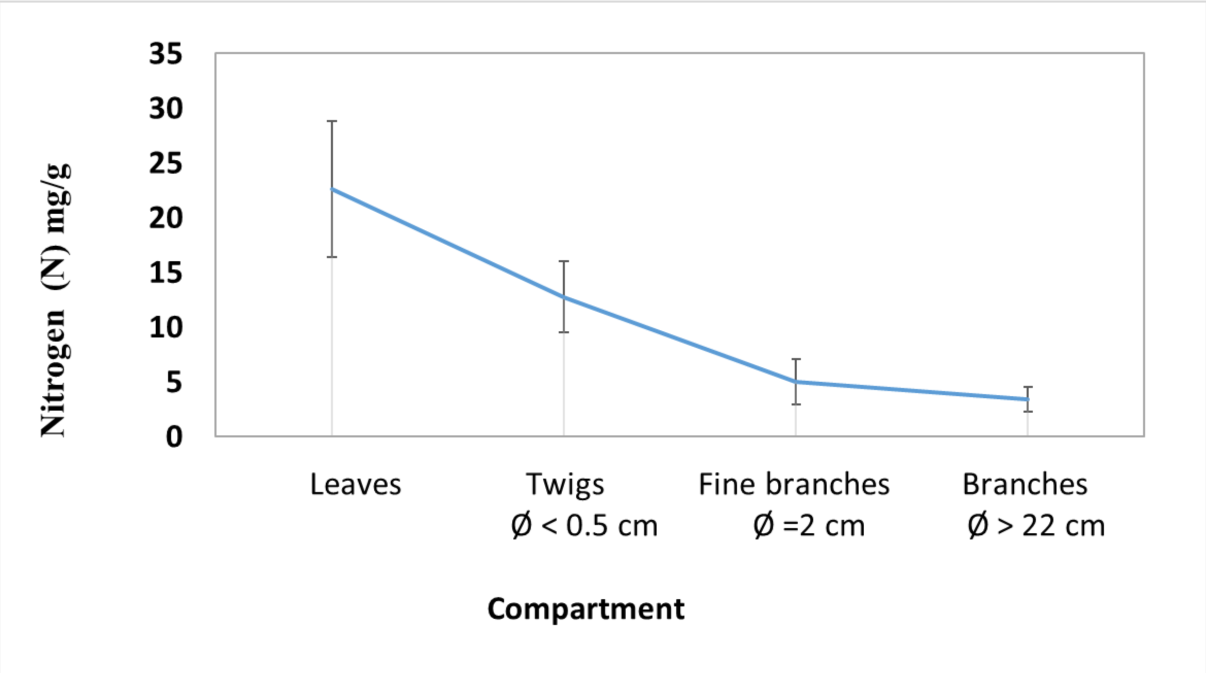
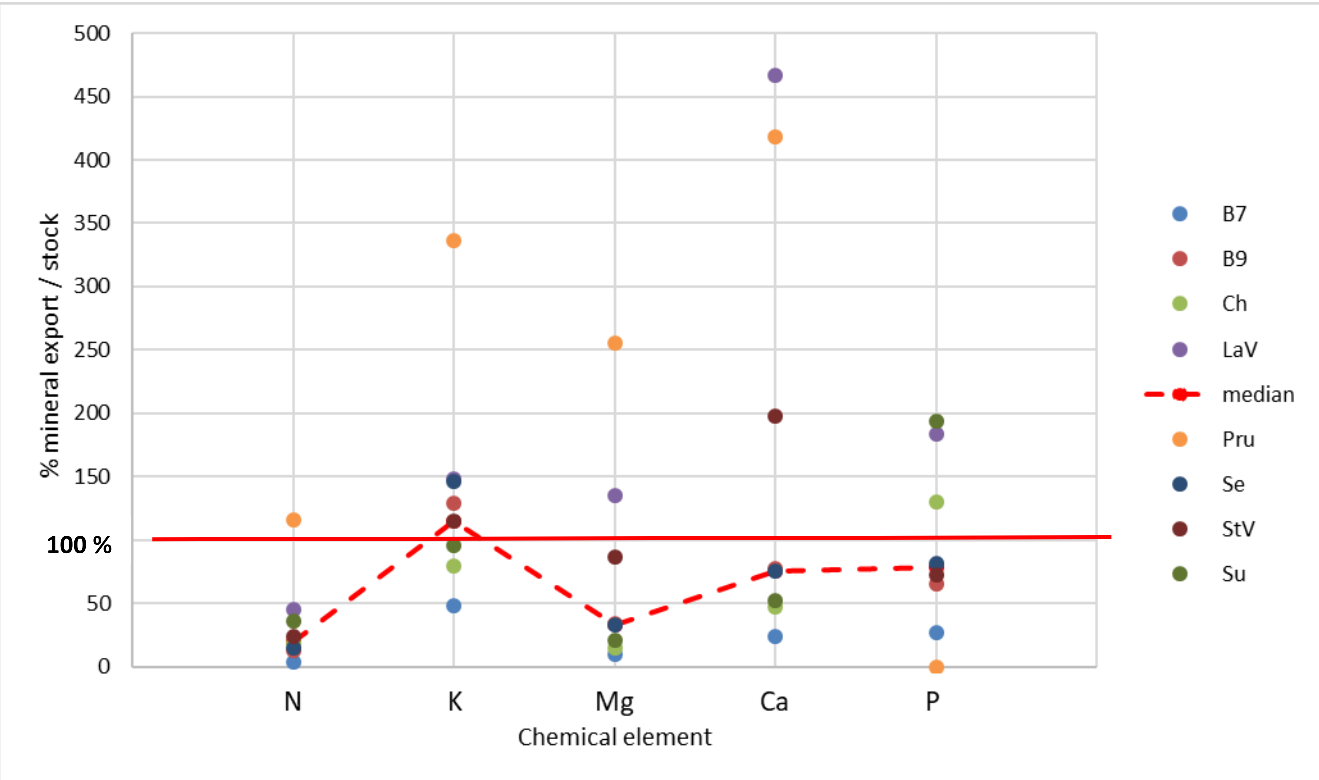


Figure 7: Average nitrogen concentrations (mg/g) for leaves, twigs, branches and wood slices sampled at the time of felling at the nine sites (according to size class) .

1.1.7 A risk assessment that takes several factors into account

We calculated the stocks of each chemical nutrient present in the surface layer of the soil (0-10 cm) at each study site to obtain a maximum threshold level for nutrient export in a single cutting operation in order to avoid impoverishing the soil. The threshold limit is usually set at 100% of the value of the stock. For five of the nine sites studied, the 100% threshold was exceeded for potassium and/or phosphorus (Figure 8), and in some cases export reached 300%. However, exceeding the threshold may not always be solely linked to soil sensitivity. For example, for two sites, export was lower than stocks for all the elements, even though soil sensitivity was high (or undetermined, depending on the element). This can be explained by the relatively low wood volume exported during the cut (less than 100 m^3 /ha, 70 t/ha), combined with very little small wood removed (20 to 25 t/ha) or large quantities residue left on the ground (more than 30%). On the other hand, for the only site located on slightly sensitive soil, the export nevertheless exceeded 100% of the stock for P because the wood volume exported was high (240 m^3/ha, 135 t/ha), a lot of small wood was removed (44 t/ha) and very little was left on the ground (7%).

The 100% threshold was most frequently exceeded for K and P. These results show **the importance of taking each nutrient into account in addition to soil sensitivity**, when assessing the risk of exporting biomass for a given harvesting operation. Special vigilance is required for potassium and phosphorus to avoid harmful consequences on ecosystem functions and the productivity of the following rotation (Bond, 2010; Achat et al, 2018; Ouimet et al., 2021).



- ***Ensure that the soil can tolerate removing small-diameter and fine wood***

In the Centre Val de Loire region, three soil classes can be distinguished on the basis of their texture in the first 10 cm: (i) soils with a predominantly sandy texture (S, SL, and LS), which are highly sensitive and where the harvesting of small trees is not recommended; (ii) soils with a predominantly clayey texture (A, AL, ALO), which are only slightly sensitive and where harvesting is possible; and (iii) soils with a predominantly silty or balanced texture, for which the level of sensitivity is difficult to predict reliably and where chemical analyses are necessary to enable foresters to make reasoned, reliable decisions. In all cases, and especially for this last category, soil analysis should be combined with appropriate harvesting volumes, as specified below.

- ***Harvest only bare trees***

To avoid exporting the nutrients contained in the foliage, trees should be harvested when they are bare; the harvesting period should therefore be shifted to the winter season, soil conditions permitting. If the trees have already leafed out, they should be left on the plot for several months so that as many leaves as possible fall to the ground (5 to 6 months are necessary for many deciduous species). Harvesting outside the growing season also has the advantage of avoiding disturbance to heritage bird species, birds of prey and black storks, during their nesting periods.

- ***Leave more wood on the ground to protect the soil***

Between 10 and 30% of the small pieces of wood should left on the ground, even more depending on the fertility of the soil and the volume of wood cut (and on other more secondary parameters). Managers can refer to the Ademe guidebook (Ademe, 2020) and the Défiforbois online application to identify soil sensitivity factors in two to five simple questions and obtain the minimum percentage of small and fine wood to leave on the ground.

- ***Adapt harvesting volumes***

Before felling, the quantity of biomass to be exported over of the next 10-15 years must be calculated on the basis of stand characteristics and soil fertility. Care must be taken to ensure that nutrients removed along with the woody biomass do not exceed soil stocks. A precise diagnosis can be made through a soil analysis and a dendrometric survey. The Défiforbois decision-support tool provides another option to help with diagnosis. The tool uses a few simple input variables relating to the stand and the soil to calculate the volume of wood that can be exported while maintaining soil fertility. This volume depends on soil nutrient stocks and stand composition.

In all cases, copses or small-diameter stems should be left to maintain vegetation cover and provide an additional food resource for game, and to help to reduce the game browsing pressure on forest regeneration.

- ***Leave downed woody debris for biodiversity***

In order to conserve deadwood for biodiversity, care must be taken to leave more than 10% of the small wood on the ground plus a few larger logs from the felling, as well as any deadwood that existed before the felling, i.e. snags, trunks and stumps already present at the start of the worksite. Brash, small wood and large lying logs are potential habitats for forest plants and animals, and therefore constitute reservoirs of biodiversity. In addition, maintaining trees that provide food resources and habitats, such as fruit trees or trees with cavities, is also favourable to biodiversity. On plots larger than 3 ha, or if the brash from a first cut will hinder subsequent silvicultural work, it is advisable to leave an uncut patch of 300 to 500 m². The patch can be set aside permenantly or repositioned at the next rotation.

2. Contribution to territorial development or transitions

The aim of the DEFIFORBOIS project was to provide recommendations and decision-making tools to guarantee sustainably managed forests in the face of increasing demands for wood, and more specifically fuelwood for energy production.

In terms of fuelwood as wood chips, whole-tree harvesting has increased sixfold since 2010 in the Centre-Val de Loire region, due to successive subsidy schemes for the biomass energy sector. In 2018, the large co-generation plants installed at Orléans and Tours consumed around 300,000 m^3 of wood chips annually. Demand is set to rise further in the coming years in response to the objectives set out in the Regional Climate Air Energy Plan (SRCAE) and the Regional Forest and Wood Plan (PRFB), and coud double from 2019 to 2025 including 188,000 t of fuelwood to supply the sixty or so new biomass heating plants expected. Theoretically, there are sufficient available upstream resources in the region, mainly in private forests, to meet the demand for wood and fibre materials that can be used for bioenergy and chemical production.

Increasing and optimising wood and woody biomass yields through productive, environmentally-friendly forest management is one of the priorities of the Regional Forest and Wood Industry Strategy. However, a number of obstacles need to be overcome in the upstream production chain. In particular, operators need to have access to appropriate equipment and human resources, as well as to relevant advice on sustainable management; and forest owners and managers need to be informed about new ways of operating and given guidance on the silvicultural changes that need to be made to remain within economic and environmental constraints.

Our technical and economic analysis of logging companies and machinery highlights the need for vigilance and improvement in terms of training and equipment over the coming years. The regional woodchip supply chain is made up of a multitude of operators (loggers, machine operators, logistics technicians and forestry technicians). These operators are grouped together within structures such as forest cooperatives or ONF Energie, but there are also many small companies (with 1 or 5 employees) scattered throughout the region. This network of companies is an asset, but it is an economically fragile one. The results of this project should help to boost the local forestry sector by encouraging logging companies to modernise, and at the same time ensure the ecological and environmental sustainability of new practices. Unlocking access to the resource and ensuring its long-term future will help to create jobs and wealth in the short and medium term. In a relatively short period of time, skilled jobs in logging companies will be needed, linked to the newly accessible resources in private forests. In the wood-energy sector alone, the additional 188,000 t objective will directly create at least 30 rural jobs, and almost as many indirectly. These jobs will maintain or even increase the vitality of the rural areas.

If we refer to the national harvesting recommendations (INSENSE) based strictly on soil sensitivity, whole-tree harvesting would only be sustainable on a very small area. Depending on the sylvoecoregion (SER), between 55% and 94% (for the Pays-Fort Nivernais and pre-Morvan plains in the east of the county, and the Sologne-Orléanais sylvoecoregion, respectively) of the sites have highly sensitive soils for which the Ademe advises against whole-tree harvesting. In the region Centre-Vel de Loire, the soil sensitivity figures make doubts on possible woodchip production in three quarters of the forested area. The DEFIFORBOIS environmental study has refined the soil sensitivity classification in the region and, above all, has taken stand and felling characteristics into account in order to define the volumes that can be harvested as whole trees without damaging soil fertility. The DEFIFORBOIS study on biodiversity expands the recommendations to include habitat protection for floral and faunal biodiversity.

The CRPF and the FCBA consider the impact of whole-tree harvesting on the soil to be of paramount importance for the sustainability of forests and in maintaining production potential in line with the needs of the forest and wood industry. The DEFIFORBOIS project in the Centre Val de Loire region has made it possible to refine and specify the operating conditions under which recommendations for maintaining fertility and biodiversity can influence fuelwood and woody biomass harvesting methods. Local disparities in soil quality, stand composition, felling regime are all factors of complexity that the GERBOISE National Research Project (Landmann et al., 2018) could not claim to address exhaustively. In this respect, working with regional players has brought useful added value.

The CNPF will be able to incorporate the recommendations for both diagnoses and management practices resulting from the Defiforbois project, into the technical advice it provides to individuals during advisory visits and collectively through meetings, training courses, publications, etc. The videos and the digital diagnostic tool for soil sensitivity, developed in the project can help to answer many questions from forest managers and owners about how to assess the risk of degradation according to soil type.

Thanks to the results obtained on its fuelwood harvesting sites monitored by INRAE, the Unisylva forest cooperative have heightened their awareness of the need to take soil into account and have incorporated the new information into revised instructions for technical staff, machine drivers and subcontractors in order to improve the environmental performance on their sites in terms of soil protection and biodiversity.

Conclusion

If we are to achieve our energy transition objectives, the forest and wood industry will have to change; at least 1.5 times more bio-based woody materials and 5 times more fuelwood will be needed, while simultaneously preserving natural processes and biodiversity.

Today, the best way response seems to be an "optimised bio-economy" with a hierarchy of uses prioritising the production of timber and industrial roundwood. This strategy will enable the carbon sequestered in forest trees to be stored in biomaterials over the long term and offers an alternative to other, much more energy-intensive materials. That said, in degraded forest stands or those that are at the end of their ecological succession, in poor coppices and coppices with standards, harvesting fuelwood provides an opportunity to regenerate with new species that are better adapted to climate change and will produce timber and industrial roundwood to fulfil longterm objectives.

Currently, the fuelwood harvested in the Centre-Val de Loire region comes from hardwood stands growing on predominantly poor soils. Our results show that whole-tree harvesting doubles nutrient exports, and that potassium and phosphorus are the elements whose stocks are most affected (Korboulewsky et al. 2020). The best way to preserve mineral elements and soil organic matter is to leave more fine woody debris in the forest by lopping crowns, leaving very small stems and preserving pre-existing deadwood stocks. This will also preserve deadwood pieces of various sizes, which is key to maintaining different types of biodiversity; deadwood variety would be lost if measures aimed solely at compensating for the export of mineral elements and carbon are applied.

In addition, the project has made it possible (1) to identify sensitive soils in the region, (2) to provide recommendations for maintaining the fertility of these soils along with habitats that are crucial for biodiversity (see visuals at https://defiforbois.inrae.fr/en-savoir-plus), and (3) to develop a digital decision-making tool (https://defiforbois-outil.efno.inrae.fr/) and communication media (https://archives.irstea.fr/defiforbois.inrae.fr/en-savoir-plus/index.html; https://hal.inrae.fr/hal-04424041/document; https://hal.inrae.fr/hal-04452025v1/document).

Ethics
The authors declare that the experiments were carried out in compliance with applicable national regulations.

Declaration on the availability of data and models
The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.
The authors used artificial intelligence for the English translation. The resulting translation was then reworked by a native English speaker (Vicky Moore).

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Authors ' contributions
Both authors participated in the elaboration and management of the project, in the field studies and data analyses, and in writing the article.

Declaration of interest
The authors declare that they do not work for, own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

Acknowledgements
The authors thank the local actors of the project (Cacot E. , Colinot A , , Renaud J.-P., Rosa J.) and the staff who helped select the forest stands for this study.
In addition, the authors thank the forestry technicians from the ONF and Unisylva for their time in preparing and carrying out the monitoring work. We also thank the forest owners who gave us the opportunity to work on their property.
We gratefully thank Infoso Unit of INRAE, and especially Richer de Forges A. for her help on the soil database and maps.
Finally, we thank Ontomantics for developing the Défiforbois digital tool, and 3dlight-studio for the graphics.

Declaration of financial support
The DEFIFORBOIS project is part of the PSDR4 programme, funded by INRAE and the Centre-Val de Loire region. All publications relating to the 33 projects in the PSDR4 programme can be viewed at: https://www.psdr.fr/

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