Forest Biofuel Biodiversity Impact Assessment

AFRY

Contracted by

Concawe

Environmental Science for European Fuel Manufacturing

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Contents

List of figures and tables

List of abbreviations

CBD	Convention on Biological Diversity
CWD	Coarse Woody Debris
DBH	Diameter at Breast Height
DG ENV	Directorate-General for Environment
EU	European Union
FMU	Forest Management Unit
GBF	Global Biodiversity Framework
Ha	Hectare
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
m^3/ha	cubic metre per hectare
MCPFE	Ministerial Conference on the Protection of Forests in Europe
NFI	National Forestry Inventory
SBTi	Science Based Targets Initiative
SBTN	Science Based Targets Network
TCFD	Task Force on Climate-Related Financial Disclosures
TNFD	Task Force on Nature-Related Financial Disclosures
WBP	Wood Based Panel
WWF	World Wide Fund for Nature

Glossary

Biodiversity: Variability of living beings of all origins including, among others, aquatic ecosystems and the ecological complexes they are a part of: this includes diversity within species and the diversity of ecosystems (Convention on Biological Diversity, 2006).

Bryophyte: Group of non-vascular land plants encompassing liverworts, hornworts, and mosses (Hedges, 2002).

Clearcutting: Clearcutting is a silvicultural system that removes an entire stand of trees from an area of 1 ha or more, and greater than two tree heights in width, in a single harvesting operation (Schönenberger & Brang, 2004)

Crown wood: Wood from the crown of a tree, which consists of the mass of foliage and branches growing outward from the trunk of the tree (Blozan, 2008).

Deadwood: Dead and decaying trees or part of trees. Types of deadwood include veteran trees, standing dead trees (snags), lying deadwood (windthrown trees or fallen deadwood) and stumps (Humphrey & Bailey, 2012).

Diameter at Breast Height (DBH): Is the standard diameter measurements at standing trees, defined at the height of 1.30 m in most countries.

Final felling: Is a process that involves the removal of the volumes of a stand or forest at the end of the rotation in an even aged management regime. Either the entire tree, including the trunk, branches, and leaves are removed when feller- bunchers and skidders are used, or only the stem is removed in the cut-to-length method (GR Tree Felling, 2023).

Fuelwood: Fuelwood is wood that is harvested from forestlands and combusted directly for useable heat in the residential and commercial sectors and power in the electric utility sector (Wright, et al., 2012). Fuelwood is usually low-quality thin branches or stem that will not be classified or used as other wood assortment for the wood industry.

Primary forestry residues: Residues generated from harvesting operations (Imperial College London Consultants, 2021). These residues are also called "Harvesting residues" when the emphasis is given as biomass source for energy purposes (Belyakov, 2019). These residues include:

1) Stem and crown biomass from early pre-commercial thinning: This category includes (thin) stems, branches, bark, needles, and leaves. These thinnings involve selective cutting of young trees that hold no value for the wood processing industry. Removing them is a routine part of forest management, promoting the growth of the remaining trees.

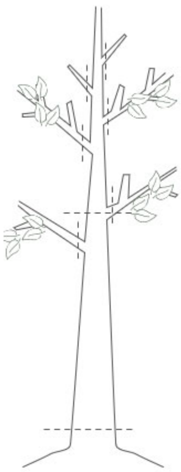
2) Logging residues from thinnings: These residues encompass stem and crown biomass, including (thin) stems, branches, bark, needles, and leaves. Thinnings, similar to pre-commercial thinnings, involve removing certain trees to enhance the growth of the remaining ones.

3) Logging residues from final fellings: This category mainly consists of branches, bark, needles, and leaves. Final fellings mark the complete harvesting of the forest stand.

4) Stump extraction from final fellings: It refers to the portion of the tree below the felling cut, including the tree roots.

5) Stump extraction from thinnings: This category encompasses the part of the tree below the felling cut during thinning operations.

Different products result from the tree stem and branches after harvesting, as summarised in **Figure 1** (AFRY 2023):



PRODUCTS	DESCRIPTION	PRODUCTS
HARVESTING RESIDUES	– Wood material which is removed during harvesting – Tree tops and branches unfit for industrial use – Partially left in the field, and also collected for bioenergy	– Biomass for energy – Pellets
SMALL DIAMETER ROUNDWOOD (PULPWOOD)	– Pulpwood or small industrial roundwood (hardwood/softwood) has a lower value than sawlogs and is the preferred raw material for pulp mills and OSB mills – Lower quality pulpwood/fuelwood is bought by the fibreboard and particleboard industry or bioenergy and firewood industry	– Paper & Packaging – Wood-based panels – Tissue – Textiles & other novel products
SAWLOGS	– The largest and highest value section of a standing tree, they have diameters of 14 cm or above, used by the sawmilling sector	– Construction – Furniture & Flooring & Doors – Wood packaging

Figure 1: Wood products resulting from the different parts of a tree: harvesting residues, small diameter roundwood (pulpwood), and sawlogs.

Raw wood: or raw wood material is wood in its natural form before being transformed to any product. Roundwood for industrial purpose such as pulpwood and sawlogs derive from raw wood (see **Figure 1**).

Relict habitat: An isolated ecosystem that remains retaining its characteristic features from the past and no longer exists elsewhere (Habel, et al., 2010).

Retention trees: living trees retained for nature consideration during clear-cut harvesting, including individual trees and small tree groups. Retaining trees will secure the input of old and dead trees in the upcoming forest generation. Retention trees are intended to remain in the forest until they are naturally decomposed. Typically robust decaying trees, hollow trees, canopy trees, those with sturdy trunk and broadleaves trees of little commercial value are trees that are important for biodiversity and classed as biodiversity value trees (Franklin, et al., 2018) (FSC, 2013).

Retention trees, retention volumes, (also retention harvesting): Also called tree retention or structural retention, these are practices in which alive mature trees are selectively retained within harvested stands at different volume levels and in different patterns (aggregated to dispersed). This practice is increasingly being used to mitigate the negative impacts of forest harvesting on biodiversity (Metsä, 2020). Harvesting residues with similar purpose may receive the classification as retention volumes.

Saproxylic: A saproxylic species depends on dead or dying wood of moribund or dead trees during some part of its life cycle (Speight, 1989).

Stem wood: The wood of the stem(s) of a tree, i.e., the above ground main growing shoot(s). Stem wood includes wood in main axes and in major branches (Camia, et al., 2018).

Thinnings: Thinning is the term foresters apply to removal of some trees from a stand to give others more room (and resources) to grow (Punches, 2004).

Threshold: the "break-point" at which there is a change in a quality

Woodfuel: Wood used as a fuel. Woodfuel may be available in a number of forms such as logs, charcoal, chips, pellets or sawdust (Humphrey & Bailey, 2012).

Summary

Concawe has contracted AFRY to better understand the biodiversity impact of producing biofuels from forest residues across Europe. The extraction of deadwood from forests has been shown that it may have a negative effect on species that depend on it for survival. To be able to determine the deadwood volumes needed to maintain viable forest species populations and the extent of forest residues that can be sustainably removed, it is necessary to gain quantifiable information on the relationship between deadwood and biodiversity. Local conditions, such as amount of deadwood present in forests and forestry guidelines and legislation also play a central role when looking for potential areas for deadwood extraction, so the scope of this study was limited to the countries in the Nordic, the Baltic, Central Europe and the Mediterranean region. The reason for the creation of these groups was founded in the types of Forest ecosystems that each group of countries and regions represents, together with the existence of an established Forest Industry.

AFRY conducted a literature review with the scientific databases Google Scholar and Dimensions, searching for scientific articles with quantifiable relationships between deadwood and biodiversity in the form of curves or thresholds. Out of a total of 1180 titles screened, 12 articles contained thresholds for deadwood and biodiversity and 28 contained a curve or a statistical model explaining the relationship between deadwood and biodiversity. The most studied species were beetles, followed by birds and fungi and most studies were conducted in Europe, mostly in Germany. Overall, studies showed a positive relationship between deadwood and biodiversity, often related to deadwood volumes but also to other deadwood characteristics, such as size or decomposition stage. Although studies showing threshold values were fewer than studies showing curves, curves and models were more complex and use a wider variety of metrics, making it difficult to aggregate and interpret results. Moreover, results were not consistent and occurrent in all countries regarding the parameters included, species focused and regions or forest ecosystems. Consequently, thresholds for specific species and countries found were considered as the most straightforward parameter for biodiversity reference and were therefore selected for the countries in which the studies were carried out: Sweden, Finland, United Kingdom, France, Germany, Austria, Switzerland, Italy, and Poland. The thresholds provided in the literature are specific to species and forest type and thus the extrapolation of them to all European forests would not be appropriate from the biodiversity perspective since parameters are referring to local habitats. Moreover, the number of studies on a European level and particularly in southern Europe, is not sufficient to provide a wide range of references with regards to biodiversity and deadwood relationship.

National Forest Inventories (NFIs) were searched for data on deadwood volumes and forest residues as well as deadwood-related guidelines and legislations. Deadwood records were included in the NFIs from the countries where the literature review provided any results in form of curve or threshold, although the available information varied in level of detail, year in which deadwood recording started, and sampling methods. Deadwood records are yet not included in all countries' inventories and when available, data on deadwood is registered on different levels of detail and covering different assortments. Guidelines on retention trees and harvesting residues retention volumes were also found, although these were often not legally binding. It is important to note that deadwood thresholds found in the literature referring to more than one species and contemplating different habitats would count as relevant and supportive criteria to consider when analysing data and parameters building up deadwood thresholds for each country. Official records of harvesting residues, harvesting volume forecasts and best practice guidelines for residue retention after harvesting operations would set the basis for estimating volume availability and residue volume restrictions for biofuels. Forest management intensity has been suggested to be a main driver of biodiversity, ecosystem processes and ecosystem services and therefore standard forest practices in the studied countries are crucial for allowing deadwood creation. Moreover, fire risk assessment

linked to deadwood levels in forests is particularly relevant, especially concerning fine branches, which contribute significantly to ignition risk on a larger scale. This is more pertinent to southern European countries due to their climate conditions, and thus should be considered when evaluating the forest health and management practices in these areas.

Concluding from this review, the establishment of deadwood thresholds that can be applied across regions and species is a challenge yet to be overcome, due to species-specific variations, regional ecological variations, data availability and research bias, and the scale and context of the studies. Nevertheless, it is crucial to follow scientifically based guidelines to ensure the protection of biodiversity. To advance the development of deadwood thresholds, the main step forward is to create a robust methodology that considers regional and species-specific variations. This approach will help determine the sustainable removal rate of forestry residues for biofuel production.

A larger and more diverse number of scientific studies are needed covering the relationship between deadwood thresholds, species, deadwood types and quality and biodiversity levels within European forests. This would allow the scientific community to establish a basis for biodiversity index development which will serve as basis for estimating biodiversity impact and developing biodiversity conservation guidelines.

1 Introduction

1.1 Project background

Concawe is interested in understanding the biodiversity impact of producing biofuels from forest waste and residues across Europe and has contracted AFRY Management Consulting ('AFRY') to complete the assessment. To date of writing the present report, Concawe has commissioned three studies in this area: one considering the overall potential sustainable availability of biofuels across Europe (Imperial College London Consultants, 2021);one concerned with the biodiversity impact of developing Miscanthus plantations for biofuel production (Fraunhofer Institute, Contracted by Concawe, 2022) and a most recent one on the examination of assessment methods for the evaluation of biodiversity impacts of forestry, with regards to future biomass provision for biofuel production (Fraunhofer Institute, contracted by Concawe, 2023).

Definitions from the wood assortments included in the Imperial College (IC) study include stem wood as the primary product obtained in forestry operations. Stem wood refers to the portion of the tree trunk that extends from the felling cut to the tree's top, with the branches removed including the bark. Apart from stem wood, the study includes various primary forestry residues that are generated throughout the process such as stem and crown biomass from early pre-commercial thinning, logging residues from thinnings; logging residues from final fellings and stump extraction (see glossary for definitions). In addition to primary residues, secondary forestry residues were also assessed in the IC study, which includes but not limited to sawmill by-products and sawdust from sawmills.

1.2 Objectives and scope

To understand the likely impact of production of biofuels from primary forest residues[1] upon biodiversity, the main objective aims to estimate the level of residue that can be removed (beyond current standard practices) without harming biodiversity and ecosystem functioning. Primary forest residues will include fuelwood and residues resulting from harvesting activities (so called harvesting residues). The previous studies commissioned by Concawe in this matter will be considered as material for discussion when results allow and are appropriate.

This document presents a literature review aiming to address the linkage of deadwood to biodiversity and ecosystem functioning, and the ways in which indexes and quantisation can be applied to identify critical residue removal levels. The initial hypothesis considers that the most suitable approach when considering the biodiversity/ ecosystem functioning impact of producing biofuels from residues, is the impact of deadwood removal, as presented in the scientific literature. Studies generally indicated higher biodiversity associated with higher deadwood volumes (Koivula & Vanha-Maimaa, 2020) (Cours, et al., 2021) (Ferenčík, et al., 2022) (Runnel & Lõhmus, 2017). The following objectives are associated with the main objective:

A) To identify key geographies within Europe for forest residue production which could feed into biofuel production and for which a forest biodiversity assessment can be performed;

B) To describe standard forestry practices (at present, and expected) in these key geographies, especially pertaining to residue removal;

[1] Primary forest residues refer to material which is collected directly from the forest to fuel production. They exclude processing residues of roundwood by the industry. (See Glossary for complementary definition)

C) To determine the biodiversity/ecosystem functioning level versus residue removal parameters and any critical levels resulting in significant biodiversity impact based on the results of the scientific studies included in the systematic literature review.

1.3 Scientific and Policy Background

1.3.1 Biodiversity awareness and frameworks

Numerous global frameworks, platforms and guidelines have been established to address habitat conservation and biodiversity, as habitat loss and degradation caused by human activities are the major drivers of biodiversity loss globally (Sala, et al., 2000). A key initiative is the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), launched in 2012. IPBES serves as an interface between the scientific community and policy makers, providing regularly updated assessments and guidance on biodiversity and ecosystem services (IPBES, 2019). Following the climate debate and the 2015 Paris Agreement, two new international cross-sector initiatives are emerging: the Task Force on Nature-related Financial Disclosures (TNFD), which builds on the Task Force on Climate-related Financial Disclosures (TCFD), and the Science Based Targets Network (SBTN), building on the momentum of the Science Based Targets Initiative (SBTi). Both initiatives support businesses and financial institutions to understand and manage their practices and impacts on nature, including biodiversity. While the TNFD is developing an integrated nature-based risk management and disclosure framework, the SBTN is working to enable companies and cities to set climate and nature targets by taking an innovative approach to finding nature-friendly solutions alongside rapid decarbonisation, and to set science-based targets that address biodiversity loss (TNFD, 2023) (SBTN, 2020).

The current understanding of biodiversity highlights the urgent need for action. Scientific research and assessments have shown that biodiversity loss is occurring at an unprecedented rate, with significant consequences for ecosystems and human well-being (IPBES, 2019). There is also an undeniable link between biodiversity loss and climate change; failure in one will have a domino effect on the other. Without significant policy change and investment, the interaction of climate change impacts, biodiversity loss, food security and natural resource depletion will accelerate ecosystem collapse. This collapse will threaten food supplies and livelihoods in climate-vulnerable economies, exacerbate the impact of natural disasters and impede progress on climate change mitigation (WEF, 2023).

The scientific community plays a vital role in understanding and addressing biodiversity issues. Scientists from a range of disciplines, including ecology, conservation biology and forestry, contribute to research, monitoring, and policy recommendations. In the field of forestry, scientists are actively investigating the impacts of deforestation, carbon sequestration, different management approaches, ecosystem functions and the role of biodiversity, among other issues. They are assessing the complex interactions between forest ecosystems and biodiversity, exploring innovative approaches to sustainable forest management, and providing valuable data for international policy development. Collaboration between scientists, policy-makers and stakeholders is essential to develop evidence-based solutions that conserve and restore forest biodiversity while promoting sustainable forest management that balances environmental, social and economic objectives (Perry, 1998) (Mubareka, et al., 2022).

1.3.2 Deadwood in European forests

The Fourth Ministerial Conference on the Protection of Forests in Europe held in 2003 adopted, within the Pan-European Criteria and Indicators for Sustainable Forest Management, nine improved indicators under the criterion 4: "Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest Ecosystems". One of these indicators included deadwood ("Indicator 4.5: Volume of standing deadwood and of lying deadwood on forest and other wooded land classified by forest type). Types of dead wood were defined, categorised and compared on a national and international level to existing assessments within monitoring schemes. The results were used to suggest a method of dead wood assessment on the scale of natural and biogeographic regions (Humphrey, et al., 2005).

Deadwood includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country (Penman, et al., 2003). Therefore, deadwood is the total amount of non-living woody biomass (necromass) in a stand, originating from the stand and from the natural processes of mortality and decay (windthrow, natural decline of old or suppressed trees) or silvicultural treatments (left crown wood, stumps, etc.) (Rondeux & Sanchez, 2010). There are different types of deadwood and wood decay stages (Figure 2).

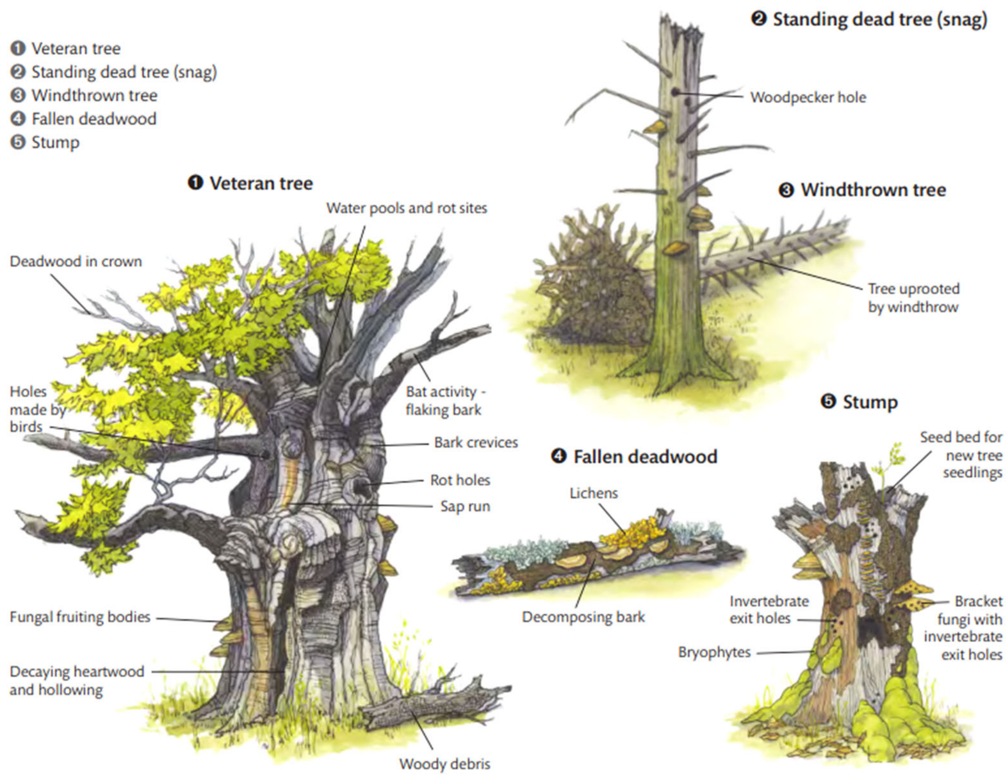


Figure 2: Different types of deadwood (courtesy of Forestry Commission UK, 2012)

Detailed definitions of deadwood components utilised in European forest inventories are as follows (Puletti, et al., 2019).

- Standing dead tree is defined as dead tree not lying on the forest floor, to be measured as Diameter at Breast Height (DBH) and total height

- Laying dead tree defines any dead trees lying on the forest floor. DBH and total height of the lying tree are measured.

- Coarse woody debris includes stems, limbs, branches lying on the floor and with a diameter at the thicker end of the debris larger than 10 cm. Coarse wood debris pieces must be detached from a trunk and not self-supported by a root system. Mandatory measures are total length and diameter at half-length.

- A stump is defined as a short vertical piece, lower than 1.3 m resulting from both cutting and natural processes. Stumps are measured in height from the ground and diameter at the top section.

Classification stages of wood decay could be defined as below and depicted in Figure 3 (Janík, et al., 2018) (Puletti, et al., 2019) (Albrecht, 1990):

1. Freshly dead (0-5 years for many species). In these stages thick and thin branches are present, the full height of stem is present unless there was damage prior to the mortality event or caused during the mortality event. The bark is present (> 80% of stem surface). Usually trees had died from suppression, bark beetle outbreak (coniferous), fungal infection (broadleaved), or those killed by fire. Tree species is still recognizable. No signs of decay are visible.

2. Thick branches are present; the tree had the full height unless there was damage prior to or during the mortality event; in coniferous trees partly barked (usually <80% of stem surface); broadleaved trees should be still fully barked, and tree species can still be identified. Less than 10% of changed wood structure. The wood only is attacked in a very small degree by wood decomposing organisms.

3. Short basal rest of main branches are recognised; full tree height unless there has been damaged prior to the mortality event; bark is missing or absent (<20% of stem surface) in coniferous species. Slightly decayed and 10-25% of the wood has a change in structure due to decomposition. This can be assessed by sticking the wood with a sharp object.

4. No branches are present or small basal rest. Tree height is <80% of the even height curve (according to DBH), tree bark is missing or absent (<20% of stem surface) in the case of coniferous species. Decomposed wood where 26-75% of wood is soft to very soft.

5. Stumps or short snags, the wood is in stages of advance rot. Very decomposed wood where 76-100% of the wood is soft.

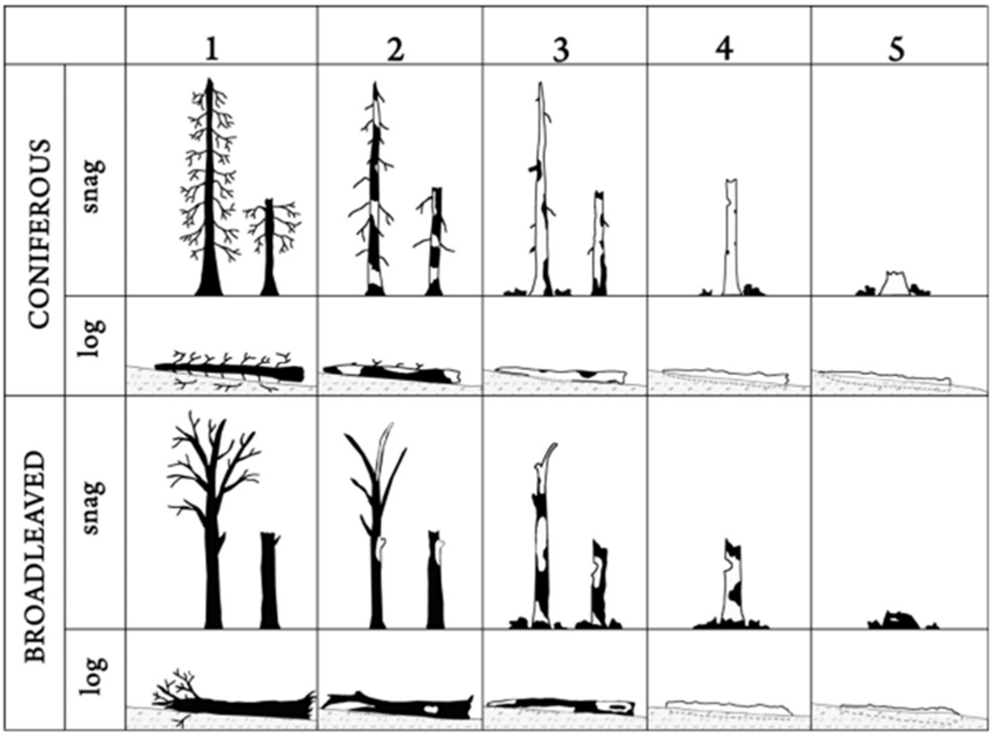


Figure 3: *Decay classes for standing and fallen coniferous and broadleaves* (Janík, et al., 2018) (Smithsonian Conservation Biology Institute, 2014).

Historically, deadwood has been removed from forests for firewood. In wood pastures and forest commons, firewood was produced from pollards, which allowed old trees with internal decaying wood habitats to develop. In most European countries, until the late 20th century, deadwood was removed from managed forests due to the need to sanitise the forest, meaning to ensure forest health, which over time has led to a widespread impoverishment of forest biodiversity. Today, the presence of deadwood in managed forests is most commonly the result of stem wood extraction not being collected for other purposes, or even stem wood after harvesting operations (Humphrey & Bailey, 2012).

Many taxonomic groups are dependent on functioning forest ecosystems, with deadwood providing an important habitat or food source for various deadwood and decaying wood dependent (saproxylic) organisms, including fungi (Ylisirniö, et al., 2012) (Junninen & Komonen, 2011), bryophytes (Arseneault, et al., 2012), beetles (Müller, et al., 2010) (Brin, et al., 2009), amphibians (Pabijan, et al., 2023), birds (Bütler, et al., 2004) and bats (Tillon, et al., 2016). Many of these species are rare or threatened and being poor colonists, and are often restricted to relict habitats[2], and ancient parkland and wood pasture where management has resulted in a continuity of deadwood over many centuries. However, while these relict habitats are of key importance, there are considerable gains to be made for biodiversity across the landscape by increasing and maintaining the amount of deadwood in all woodlands, including conifer plantations (Humphrey & Bailey, 2012).

[2] Relict habitats: An isolated ecosystem that remains retaining its characteristic features from the past and no longer exists elsewhere

1.3.3 Residues extraction potentially conflicts with conservation values

Since forests in central Europe are amongst the most utilised ecosystems on Earth (Lassauce, et al., 2011) (Hannah, et al., 1995), the increased production of renewable energy, and therefore the demand for biofuel from forestry feedstocks, raises questions regarding the effect of these practices on managed forests ecosystems and the impact on biodiversity (Bauhus, et al., 2009). By increasing consumption of woody residues and reducing the amount of woody debris in forest ecosystems, in any of its forms – snags, stumps, downed fine and coarse woody debris and deadwood attached to trees, the effect of forest management particularly affects these organisms and hence forest management guidelines are put in place to conserve certain biodiversity levels (Siitonen, 2001).

Woodfuel production initiatives and harvesting should therefore comply with current forestry environmental standards and guidelines and be carefully targeted to avoid high value deadwood areas wherever possible. In low-value areas, such as clear-fells in plantations, clustering of deadwood in specific retained groups or patches across the coupe will allow for the development of deadwood habitats (Table 2), while providing scope for removal of woody debris for woodfuel on non-retained portions of the coupe.

To conduct residue extraction activities that comply with biodiversity conservation and standards, species habitat conditions thresholds must be taken into consideration. The scientific community has targeted this topic and studied different forms to understand the requirements of certain species to remain in a particular ecosystem over time, i.e., to be preserved. There have been studies trying to determine the deadwood requirements in a forest area for certain species and develop threshold approaches, this means obtaining ranges rather than exact values when considering different species and assemblages (Ranius & Fahrig, 2006). Previous literature reviews searching for relations between deadwood and biodiversity have established that the available literature focuses mostly on beetles, bryophytes and fungi, and that information on further taxa is lacking to be able to include in a meta-analysis (Paillet, et al., 2009). To date, there is no exact universal amount of deadwood that should be left in forests for saproxylic species to thrive, as each species groups show general differences in habitat requirements, and therefore in need of a variety of conservation measures (Brunet, et al., 2010).

Deadwood volume per area, commonly measured in m^3/ha, is the most common metric used to measure the change in species and individual richness of the studied organisms. This standard indicator is currently being widely used to assess the effects of forest management or conservation policy (Rondeux & Sanchez, 2010).

Results from 2010 showed a weighted average volume of total deadwood (the sum of both standing and lying deadwood), which was about 10 m^3/ha for Europe (Schuck, et al., 2015). The estimates for standing and lying deadwood at a country level ranged between 5 and 15 m^3/ha for most countries. Belarus and the United Kingdom reported values below 5 m^3/ha whereas Lithuania and Ukraine reported figures above 20 m^3/ha and Slovakia reported a very high average amount of standing and lying dead wood of 40 m^3/ha. With regards to deadwood distribution, lowest amounts of deadwood can be found in floodplains and swamp forests and in forests with introduced species. High amounts can reportedly be found in alder (not riverbanks), birch or aspen forest, and in Alpine coniferous forests.

Nevertheless, further deadwood characteristics, such as decomposition class, diameter, or basal area, play a role in the habitat use intensity of saproxylic species (Arseneault*, et al*., 2012) (Martin, et al., 2021), and studies have emphasized the importance of deadwood quality and diversity of tree species for the maintenance of saproxylic abundance and richness (Brin, et al., 2009). Regarding the targeted species, number of species is a commonly used variable, but others such as occurrence, number of individuals or density are also used in studies including thresholds (Müller & Bütler, 2010).

1.3.4 National Forestry Inventories and policies related to deadwood

Deadwood is generally present in lower volumes in conventionally managed forests in comparison to natural forests (Siitonen, et al., 2000) (Nagel, et al., 2017) (Dieler, et al., 2017), with the quantity of deadwood in managed forests being between 2% and 30% of the quantity of deadwood in unmanaged forests (Fridman & Walheim, 2000). Deadwood is a relatively new variable for most National Forest Inventories (NFI) in Europe, and more complex than other forest variables, such as stand structure, vegetation and stand age (Rondeux & Sanchez, 2010). Therefore, problems arise related to data collection and processing protocols, as well as to cross-country harmonization (Rondeux, et al., 2012). Since management practices aiming at deadwood enhancement have been applied only for less than 30 years, detailed information on deadwood quantities is still unavailable in many countries. Moreover, monitoring to provide this kind of information has not been part of national forest inventories in some countries (Vítková, et al., 2018).

In the 2003 MCPFE Report on Sustainable Forest Management in Europe, deadwood was already approved as a quantitative indicator for "Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest Ecosystems", with its indicator being "Volume of standing deadwood and of lying deadwood on forest and other wooded land classified by forest type" (MCPFE & UNECE/FAO, 2003). However, to be able to make appropriate decisions on policies and forest management, it is necessary to establish a robust theoretical basis, be familiar with trends and be able to evaluate the consequences of measures taken (Noss, 1999) (Carpenter, et al., 2006). Furthermore, in international and European political processes, WWF already reported in 2004 that deadwood was increasingly being accepted as a key indicator of naturalness in forest ecosystems. This implies governments which have recognised the need to preserve the range of forest values and are committed to these processes, can help reverse the current decline in forest biodiversity. This can be achieved by including deadwood in national biodiversity and forest strategies, monitoring deadwood, introducing supportive legislation and raising awareness (WWF, October 2004).

In 2011 the European Union (EU) established its Biodiversity Strategy, aiming to halt biodiversity loss by 2020. Among agreed targets and actions, Action 12 in the strategy relates to integrating biodiversity measures in forest management plans, and states that one measure is "to maintain optimal levels of dead wood" (EU, 2011). The strategy does not define "optimal levels" in quantitative terms, but explicitly refers to the EU Species and Habitat Directive that calls for "Favourable Conservation Status" (FCS) for listed habitat types and species. This highlights the need for better baseline information on dead wood availability in different forest types and setting the current volumes in relation to the demands of saproxylic species (Travaglini, et al., 2007).

The European Commission has put forward the Nature Restoration Law (adopted by the EU Council in June 2024) that represents the first comprehensive law of its kind at a continental level. Aligned with the EU Biodiversity Strategy, the law aims to establish binding targets for the restoration of degraded ecosystems, with a particular emphasis on those capable of sequestering carbon and mitigating natural disasters. Forest ecosystems are a primary focus among the proposed targets, which specifically address Member States to "achieve an increasing trend for standing and lying deadwood, uneven aged forests, forest connectivity, abundance of common forest birds and stock of organic carbon".

There are a number of ways to increase the creation of deadwood habitats. Artificially injuring or felling trees and leaving some felled trees and logs when thinning can be very beneficial in areas of low ecological value, such as forest plantations. Artificial snags and high stumps can be created by using a harvester head to cut the top of the tree and remove the foliage to a height dependent on machine capabilities and safety (Forestry Commission, 2017). These management practices are implemented in some geographies by large industry players like Stora Enso and Tornator in the Nordics.

1.3.5 Deadwood and fire risk

The current policy discussions in both the Nature Restoration law and EU Forest policy have included a request by the Directorate-General for Environment (DG ENV) of the European Commission to explore the link between deadwood and fire risk in Europe. The platform of the project called "Bioagora" hosted the request. Bioagora is a collaborative 5-year European project funded by the Horizon Europe programme. It aims to connect research results on biodiversity to the needs of policy making in a targeted dialogue between scientists, other knowledge holders and policy actors (Bioagora, 2023). The Bioagora framework aims to identify a) links between deadwood characteristics and fire risk in the different biogeographic regions of Europe, and b) forest management approaches for reconciling the biodiversity objectives of deadwood management with forest fire risk prevention. Fire risk was defined as both the likelihood of a fire and its intensity if it occurs. The likelihood is dependent on probability of ignition and spread of fire, and human structures are not considered to influence the risk.

Therefore, DG ENV requested a synthesis of knowledge within Experts gathered by Bioagora submitted the report "Deadwood and Fire risk in Europe" on 17th of July 2023 (Larjavaara, et al., 2023), which explains that the volume of dead wood generated by natural disturbances is highly variable among European forest ecosystems and can represent a large portion of the fuel available to burn during a forest fire. However, large pieces of deadwood such as lying trees burn slowly and therefore contribute only little to fire intensity. On the other hand, fine fuels such as branches and dead needles, attached to deadwood can have a significant effect on fire intensity. Salvage logging (cutting and removing timber after disturbances), which usually aims to reduce fuels and intensity of potential future fires (Müller, et al., 2010) after a large-scale natural disturbance does not normally reduce the amount of fine fuels and may therefore not reduce fire risk (if still woody residues are left on the field) but the likelihood of expanding

Important for fire risk estimation is the surface to deadwood volume ratio. Large pieces imply little fire risk even when their volume is high in a large surface. More deadwood relative to more intensive forestry could increase fire risk.

In areas with a high risk of severe fires (e.g., close forest canopy), specific treatments such as thinning and the partial removal of deadwood at strategic points would be necessary to prevent wildfire spread. Large areas with high loads of deadwood cover should be fragmented by wildfire protection corridors (Forestry Commission, 2014). As for the fuel breaks in place, the protection corridors should have the number of standing trees per hectare reduced and surface fuels removed.

Maintenance of wildfire protection corridors would be achieved by regularly removing surface material (litter layer, grass-herb and litter layer, understory/natural regeneration) by mechanical treatment (e.g., shredding fire fuels and thus creating compact layers of organic material, which would maintain soil moisture and lower-level fuel moisture), by prescribed grazing (silvopastoral or other agroforestry land use) or prescribed burning (Goldammer, et al., 2020).

Particularly in Mediterranean regions, deadwood is important for biodiversity as these ecosystems are characterised by low nutrient availability and frequent drought periods. Mediterranean forest-types are the European ecosystems more prone to wildfire risk both currently and under the predicted climate change scenarios (Larjavaara, et al., 2023).

The presence of deadwood should be increased in the Mediterranean forests to ameliorate biodiversity (Larjavaara, et al., 2023)(Bioagora, 2023). A potential way to conciliate this objective with fire prevention would be to focus on the conservation of large pieces of deadwood (e.g., > 17.5 cm) (Larjavaara, et al., 2023) as they are the ones more valuable from a biodiversity point of view and the least problematic for wildfire risk. In European temperate forests, the correct balance between standing, fallen and stump deadwood and wildfire prevention has been defined in some countries' guidance (Forestry Commission, 2014). However, further research is needed to provide the empirical evidence necessary for helping decision making. In boreal Europe, important fuels in surface fires include mosses, lichens, and litter such as dry needles (Tanskanen, et al., 2007). Litter decomposes fast relative to its production and does not generally accumulate on the forest floor. In boreal Europe, the fire season is short and typically lasts on average only a few weeks peaking in June (Larjavaara, et al., 2004). Crown fires are rare in boreal Europe but could potentially develop under extreme weather conditions in dense stands, especially in spruce stands. It is unlikely that deadwood would significantly increase the risk of ignition or spread of a surface fire. Considering general knowledge on fire behaviour, the report concludes that it is likely that in most cases large deadwood assortments do not significantly contribute to fire risk, which has discouraged fire scientists from conducting experimental studies. More significant fire risk is understood to be allocated to deadwood branches and leaves, compared to larger diameter deadwood as these assortments are believed to contribute to the fire intensity. Further experimental studies would be recommended to provide more in-depth knowledge of the deadwood assortment proportion and balance in the forest facing fire risk. This means, if the removal of small deadwood assortments would be more favourable for fire risk prevention, emphasising the presence of higher volumes of larger diameter deadwood for biodiversity conservation purposes on European bioregions and forest types.

1.3.6. Deadwood as a forest carbon pool

Deadwood is included in the list of the five carbon pools provided by the Intergovernmental Panel on Climate Change (IPCC)- Good practice guidance for Land Use, Land Use Change and Forestry (above-ground and below-ground biomass, litter, deadwood and soil) (Penman, et al., 2003).

Carbon stocks and types and forms of deadwood are a critical component of forest Carbon dynamics. Dead wood accounts for ~8% of total Carbon pool in forests globally (Martin, et al., 2021). There is variability between different types of forest, which is attributable to differences in primary production, tree mortality, and decomposition rates that are linked with climate and species' wood composition (Luyssaert, et al., 2007). The dynamics of deadwood carbon can be sensitive to other local disturbances such as harvesting regimes, windstorms, wildfires, and pest outbreaks (Luyssaert, et al., 2007).

There is variability in the patterns of deadwood change of carbon fraction through decay processes; e.g. cellulose and hemicellulose generally decompose more rapidly than lignin (Harmon, et al., 2013), but lignin has a higher carbon concentration (60%) than cellulose and hemicellulose (40%), the latest decomposing more rapidly than lignin (Luyssaert, et al., 2007).

Deadwood volumes in the forest do not only contribute to ameliorate biodiversity levels but it is part of the carbon cycle and the carbon dynamics and therefore consider a carbon pool in the forest ecosystem.

2 Methodology and Approach

2.1 Literature review

To better understand the effect of residue removal, AFRY conducted a systematic literature review to investigate the scientific based functional link between deadwood and biodiversity. The main objective was to identify pre-defined thresholds for individual geographies, indicating the point where residue removal would impair species populations and ecosystem function. To date, there is no comprehensive study on sustainable levels of residue removals impacting biodiversity in the forest.

The review was designed to provide a baseline of current scientific knowledge in this field. We expected that functional relationships between deadwood and biodiversity differed when comparing different geographies and ecosystems.

To localize any relevant studies, we identified key regions for residue production throughout Europe and ranked them based on forest types, forest industry size (as a proxy for potential residue availability), as well as proximity and scale of potential biofuel processing centres:

- **Region A: Nordics:** Sweden, Finland, Norway
- **Region B: Baltics**: Lithuania, Estonia, Latvia
- **Region C: Central and Western Europe:** Germany, France, Switzerland, Austria, Poland, United Kingdom
- **Region D: Mediterranean countries:** Iberia, Italy

Google Scholar and Dimensions (Digital Science, 2018) were used as searching engines. We followed a five-stage approach for article selection:

1) Title long list: *Articles were selected if they contained words relating to deadwood and biodiversity in their headline.*

2) Abstract short list: *If the abstract described a relationship between deadwood and species or ecosystem function, the article was selected for full-text acquisition.*

3) Article selection based on:
    a. A relationship between deadwood/harvesting residues and biodiversity/ecosystem functioning had been established
    b. Quantifiable relationship between deadwood and biodiversity/ ecosystem function had been detected (i.e., a threshold or a regression curve)

4) Rating: The articles were rated according to the following by rating.
    a. Quantifiable relationship detected: 1 (excellent)
    b. General relationship detected: 2 (good)
    c. Info on deadwood requirements for biodiversity: 3 (moderate)
    d. Only vague information on deadwood and biodiversity: 4 (poor)

    If both questions of section 3 were answered with "yes", the article was rated 1 (excellent). If only one was answered with "yes", the article was rated 2 (good). If the article provided information on general deadwood/residue requirements for ecosystem function, the article was rated 3 (moderate). If the article included deadwood/residues and endangered species the article was rated 4 (poor).

5) Extracting data: For all articles rated "excellent" and "good", information was collected on:
    a. the region and country in which the study was conducted,
    b. forest and/or tree species at the study site,
    c. type of forest management at the study site,

d. *organisms studied,*
e. *IUCN Red List information on studied organisms*
f. *if available, the deadwood threshold needed to maintain the studied organism and/or*
g. *the biodiversity index/regression curve representing the relationship between deadwood characteristics and the studied organisms.*

Studies meeting the "5-Stage" criteria outside Europe were only included if the vegetation and climate of the study site was comparable to that of the target areas.

<u>Searches</u>

Initial screening

We used Google Scholar for an initial literature search to identify the linkage between deadwood and biodiversity and ecosystem functioning in different European countries and regions. Google Scholar allows the use of terminologies in different languages addressing local publications that were considered when relevant. The screening was performed in April 2023, and we considered all articles published 1990 or later. For the search, the keywords and language detailed in the table below were used. For selection stage 1, the words "deadwood" or "dead tree" or "residues" or "coarse debris" or "biodiversity" or "species richness" or "species diversity" or "diversity" (related to a species or species group) had to be in the title for the article to be selected for stage 2. After carrying out all 5 stages, the search yielded 17 articles rated 1 or 2 (Table 1, indicated as Final). Table 1 details the obtained number of articles for each search, number of articles selected by title, selected by abstract and final articles including relevant information on thresholds and biodiversity.

Table 1: Search terms used for Google Scholar search.

<table>
<tr><th>Searching words</th><th>Language</th><th>Results</th><th>Selected by title</th><th>Selected by abstract</th><th>Final</th></tr>
<tr><td>"deadwood" AND "biodiversity" AND "threshold" AND "Spain"</td><td>English</td><td>2640</td><td>950</td><td>10</td><td>8</td></tr>
<tr><td>"madera muerta" AND "biodiversidad" AND "Iberia"</td><td>Spanish</td><td>552</td><td>1</td><td>1</td><td>0</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "biodiversity"</td><td>English</td><td>11600</td><td>40</td><td>9</td><td rowspan="4">2</td></tr>
<tr><td>"Totholz" AND "Schwellenwert" AND "Biodiversität"</td><td>German</td><td>302</td><td>40</td><td>6</td></tr>
<tr><td>"Deadwood" AND "conservation" AND "biodiversity"</td><td>English</td><td>24300</td><td>30</td><td>8</td></tr>
<tr><td>"Totholz" AND "Naturschutz" AND "Biodiversität"</td><td>German</td><td>2150</td><td>20</td><td>4</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Sweden"</td><td>English</td><td>4690</td><td>64</td><td rowspan="7">112</td><td rowspan="7">5</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Norway"</td><td>English</td><td>4450</td><td>4</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Finland"</td><td>English</td><td>3470</td><td>17</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Lithuania"</td><td>English</td><td>615</td><td>19</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Latvia"</td><td>English</td><td>609</td><td>18</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Estonia"</td><td>English</td><td>1030</td><td>2</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "Europe"</td><td>English</td><td>22400</td><td>19</td></tr>
<tr><td>"Deadwood" AND "threshold" AND "biodiversity" AND "Central Europe" AND "harvesting residue" AND "species"</td><td>English</td><td>7170</td><td>90</td><td>51</td><td>2</td></tr>
<tr><td>"Dead wood" AND "threshold" AND "Great Britain" AND "biodiversity" AND "UK"</td><td>English</td><td>24000</td><td>2</td><td>2</td><td>0</td></tr>
</table>

Main Screening

For the main literature query, Dimensions was used in English language. The review was conducted following the guidelines for systematic reviews in environmental management (CEE, 2013). We restricted the search to peer-reviewed scientific papers. The search was conducted on 21st April 2023. All peer-reviewed articles published in 1990 and later were considered. The following expression was used in the search:

((deadwood AND biodiversity) OR
(deadwood AND ecosystem) OR
(deadwood AND species) OR
(deadwood AND harvesting residues) OR
("coarse debris" AND biodiversity) OR
("coarse debris" AND ecosystem) OR
("coarse debris" AND species) OR
("coarse debris" AND harvesting residues) OR
("decay wood" AND biodiversity) OR
("decay wood" AND ecosystem) OR
("decay wood" AND species) OR
("decay wood" AND harvesting residues))

The search yielded 1180 articles, which were classified following the 5-stage approach. For stage 1, the words "deadwood" or "dead tree" or "residues" or "coarse debris" or "biodiversity" or "species richness" or "species diversity" or "diversity" (related to a species or species group) had to be in the title for the article to be selected for stage 2. 331 articles were selected in stage 1 and 98 articles were selected in stage 2. After ranking the articles, 29 studies were ranked with "2" and 29 studies were ranked with "1" (Table 2).

Table 2: Number of articles for each stage of the first Dimensions search.

Search Result	Title long list	Abstract short list	Articles rated "2 – good"	Articles rated "1 - excellent"
1180	331	98	29	29

Second literature search

A second literature search was conducted at the beginning of May 2023 following additional search term recommendations by Concawe. Dimensions was used with the same temporal parameters and the following expression.

(deadwood AND forest ecosystem) OR
(deadwood AND biodiversity method) OR
(harvesting residue AND biodiversity) OR
(deadwood AND harvesting residues) OR

The search yielded 1184 articles. The 5-Stage approach for article selection was conducted with minor changes. This time, in Stage 1 – Selection by title, articles containing the words "forest ecosystem", "method" and "residue" were selected. 41 articles were selected by title and after discarding those articles already present in the previous searches, 4 articles were selected for reading. Only one article was included within the "5-Stage" criteria and was rated as "1" (Table 3).

Table 3: Number of articles for each stage of the second Dimensions search.

Search Result	Title long list	Abstract short list	Articles rated "2 – good"	Articles rated "1 - excellent"
1184	41	4	0	1

Other articles

Articles provided by Concawe (Table 4) and additional wildcard finds were also taken into consideration for the study. It was checked whether the articles had already been included through the scientific databases search, and those articles that had not previously appeared went through the 5-Stage approach.

Table 4: Articles provided by Concawe and included in our analysis.

Title	Reference
Deadwood volumes matter in epixylic bryophyte conservation, but precipitation limits the establishment of substrate-specific communities	(Kropik, et al., 2021)
Quantifying consequences of removing harvesting residues on forest soils and tree growth – A meta-analysis	(Achat, et al., 2015)
Effect of deadwood management on saproxylic beetle richness 3 in the floodplain forests of northern Italy: some measures 4 for deadwood sustainable use	(Della Rocca, et al., 2014)
Effects of forest management on the diversity of deadwood-inhabiting fungi in Central European forests	(Blaser, et al., 2013)
Rebuilding green infrastructure in boreal production forest given future global wood demand	(Moor, et al., 2022)
Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe	(Gao, et al., 2015)
Saproxylic species are linked to the amount and isolation of dead wood across spatial scales in a beech forest	(Haeler, et al., 2021)
The role of nature reserves in preserving saproxylic biodiversity: using longhorn beetles (Coleoptera: Cerambycidae) as bioindicators	(Karpiński, et al., 2021)

<u>Data analysis</u>

Data extracted during the "5-Stage" approach of article selection including:

i.) country in which the study was conducted,
ii.) organism the study focused on and
iii.) whether the studied organisms were listed as endangered, was used to visualize the number of studies conducted in specific regions and on specific organisms.

Results from the systematic literature review will be considered to identify the regions and countries within Europe to be selected for further analysis.

2.2 Deadwood quantification in Europe

Quantification of deadwood in European countries is a recognised indicator of measuring biodiversity and thus levels of deadwood in the forest will influence the habitat biodiversity levels (Ministerio para la Transición Ecológica y el reto Demográfico, 2008). This has been considered a reference point for this study.

Deadwood records within forest inventories were investigated in the 4 regions included in the scope of this study. The aim of this exercise is the identification of any biodiversity awareness related to deadwood, and potential guidelines set in these countries for the deadwood conservation in the forest. The different National Inventories sources are summarized in the table 5.

Table 5: Sources of National Forestry Inventories (NFIs) by country

Country	*Source*
Germany	Dritte Bundeswaldinventur (Bundeswaldinventur, 2012)
Austria	Österreichische Waldinventur (Bundesforschungszentrum für Wald, 2016/21)
Switzerland	Schweizerisches Landesforstinventar (Brändli, et al., 2020)
Norway	A century of National Forest Inventory in Norway – informing past, present, and future decisions (Breidenbach, et al., 2020)
Sweden	Deadwood availability in managed Swedish forests – Policy outcomes and implications for biodiversity (Jonsson, et al., 2016)
Finland	Forests of Finland 2014-2018 and their development 1921-2018 (Korhonen, et al., 2021).
Estonia	Metsastatistika (Keskkonnaministeerium, 2023)
Latvia	National forest inventory (Silava, 2023)
Lithuania	Nacionalinė miškų inventorizacija (Valstybinė miškų tarnyba, 2022)
Poland	How much, why and where? Deadwood in forest ecosystems: The case of Poland (Bujoczek, et al., 2021) (Bujoczek, et al., 2021) (Bujoczek, et al., 2021)
France	Le supplément d'ign magazine sur l'information forestière (IGN, 2012)
Italy	Italian National Forest Inventory—Methods and Results of the Third Survey (Gasparini, et al., 2022) (Gasparini, et al., 2022)
Spain	Cuarto Inventario Forestal Nacional (Ministry of the Environment, Rural and Marine Affairs, 2008)
Great Britain	National Forestry Inventory (Forest Research, 2023)

Environmental policies containing information on deadwood were considered for biodiversity awareness and the existence of any restrictions or guidance in extracting woody residues in the forest after harvesting operations (Table 6), together with any existing guidelines indicating retaining harvesting volumes for the purpose of deadwood creation.

Table 6: Sources of deadwood-related policies by country

Country	Source
Germany	Bundesnaturschutzgesetz (Bundesministerium der Justiz, 2009); VNPWaldR 2007 (Bayerische Staatsministerien für Umwelt und Gesundheit sowie für Ernährung, Landwirtschaft und Forsten, 2010); Landesnaturschutzgesetz – LnatSchG NRW (Ministerium des Innern des Landes Nordrhein-Westfalen, 2023); Waldgesetz für Baden-Württemberg (Landeswaldgesetz – LwaldG) (Landesrecht BW, 2023); Drittes Bundeswaldinventur (Bundeswaldinventur, 2012)
Austria	Naturschutzpraxisbuch – Naturschutzmaßnahmen als Beitrag zum Ökologischen Landschaftsmanagement (Österreichische Bundesforste AG, 2017)
Switzerland	Waldpolitik 2020 (Bundesamt für Umwelt, 2011); Strategie Biodiversität Schweiz (Bundesamt für Umwelt, 2012); Botschaft zur Änderung des Bundesgesetzes über den Wald und zur Volksinitiative «Rettet den Schweizer Wald» (Bundesamt für Umwelt, 2007)
Norway	Act relating to forestry (Forestry Act) (Ministry of Agriculture and Food, 2005) ;Norwegian PEFC Forest Standard (PEFC, 2015)
Sweden	The FSC National Forest Stewardship Standard of Sweden (FSC, 2019); The Swedish Environmental Objectives – Interim Targets and Action Strategies: Summary of Government Bill 2000/01:130 (Swedish Ministry of Environment, 2001) ; Skogsvardslagstiftningen gallande regler 1 september 2022 (Skogsstyrelsen, 2022); Skogsstyrelsens föreskrifter och allmänna råd till Skogsvårdslagen (SKSFS 2011:7, 2011)
Finland	Metsänhoidon suositukset (Äijäla, et al., 2019); Criteria for PEFC Forest Certification. PEFC FI 1002:2014 (PEFC, 2014); Forest Act (1093/1996; amendments up to 567/2014 included) (Ministry of Agriculture and Forestry, Finland, 2014)
Estonia	NEPCon Ajutine Metsamajandamise Standard Eestis (NEPCon, 2014)
Latvia	The FSC Interim Forest Stewardship Standard for Latvia (FSC, 2023)
Lithuania	The FSC National Forest Stewardship Standard of Lithuania (FSC, 2020)
Poland	Odnawialnych źródłach energii (OZE, 2017)
France	Le supplément d'ign magazine sur l'information forestière (IGN, 2012)
Italy	Il rilascio di alberi a tempo indefinito nella gestione forestale: una proposta per adeguare le normative regionali. (Dondini, et al., 2008)
Spain	“Preliminary ecological bases for the conservation of habitat types of Community interest in Spain” (Ministry of the Environment, Rural and Marine Affairs, 2009)
Great Britain	Managing deadwood in forests and woodlands. Forestry Commission Practice Guide (Humphrey & Bailey, 2012); The UK Forestry Standard – The governments’ approach to sustainable forestry (Forestry Commission, 2017); UK Woodland Assurance Standards (UKWAS, 2018)

2.3 Forest residues analysis – considerations

Forest residues, or “primary forest residues” are leftovers from harvesting operations after clear cutting, selective harvesting or thinning. They can be either crown tops, branches, stems, or thin diameter trees. Depending on the presence of an available market for these residues, they can be either left in the forest becoming deadwood over time or be collected for commercial use (see Glossary).

Natural, close-to-nature forest and forest with minimal intervention and not ongoing forest management (with reduced activities like only final extraction with e.g., no thinning) have not been considered in this study as the volume of the harvesting residues or wood residues will not be significant, due to limited operations compared to the volumes derived from productive forest areas. It is understood that the biodiversity impact of removing current deadwood from those areas will be higher, as it will imply the removal of already developed ecosystems for saproxylic species; moreover, legal restrictions to deadwood extraction might be in place in those areas.

Public statistics on harvesting residues have been considered for each country within the key regions. Countries not presenting records of this wood assortment have been discarded for further selection as it is understood either that there are no policies in place for acquiring this data or the supply chain is still in maturity. Official references and deadwood thresholds provided by the scientific literature will provide the framework to estimate biodiversity impact on those forest areas when residues are removed.

National inventories and statistics from Austria, Germany, France, Switzerland, Finland, Sweden, Spain, Italy, Norway, Baltics and United Kingdom have been consulted on recording of harvesting residues volumes.

3 Key findings

3.1 Main results from literature review

Out of all articles ranked "1" or "2", approximately 89% were original research articles, of which approximately 90% were carried out in Europe and 10% in North America. Within the European studies, almost half of them were carried out in Central Europe, followed by Northern Europe with 20% of the locations of the studies. The most represented countries were Germany (23%), France (14%), Sweden (10%) and Poland (10%) (Table 7).

Table 7: Number of highly ranked articles by country.

Europe	Sweden	6
	Norway	1
	Estonia	1
	Finland	1
	Denmark	1
	Germany	15
	Poland	6
	Austria	2
	Switzerland	1
	Czech Republic	1
	Slovakia	3
	France	9
	Italy	5
	Spain	3
	Multiple countries	7
North America	Canada	5
	USA	1

Invertebrates were the most studied organisms, especially saproxylic beetles (41% of studies), fungi (17%) and birds (16%). Approximately 12% of the studies targeted multiple taxa and the remaining studies analysed the relationship between deadwood and other invertebrates (7%), plants and lichens (4%), amphibians (1%), and bats (1%) (Table 8).

Table 8: Number of highly ranked articles by species targeted

Species	**N° articles**
Birds	11
Amphibians	1
Bats	1
Beetles	28
Bees	1
Microinvertebrates	1
Macroarthropods	1
Gastropoda, Isopoda, Diplopoda	1
Insects (general)	1
Fungi	12
Plants and lichens	3
Multiple taxa	7

12 different thresholds from original research articles were found. 3 out of the 12 studies refer to beetles, and 3 others describe a relationship between deadwood and birds. The rest of the threshold found refer to other insects, bryophytes, fungi, and bats. One study analysis specifies the relationship of deadwood with species of conservation concern. In total, 8 studies include red-listed or rare species in their research. Most studies were carried out in Central

and Northern Europe, and the remaining studies were carried out in Italy and France (Table ***9***).

The thresholds were mostly interpreted from curves describing the relationship between species richness and deadwood amount, often derived from statistical models, such as Generalized Additive and Linear Models used to assess which variables are stronger predictors for the presence of a species (Table 10). Additionally, further 28 original research articles were found containing curves illustrating a relation between deadwood and biodiversity. These curves did not provide with any deadwood thresholds but were relevant as evidence to prove relationship between deadwood and biodiversity. Out of these studies, 24 were carried out in Europe and only 4 in North America. The most represented European country was Germany (8 studies). Regarding the species studied, approximately half of the curves (11 curves) illustrated a relationship between deadwood and beetles, followed by fungi (5 curves). Red-listed species were considered in 10 of these studies. All studies show a statistically positive relationship between biodiversity and deadwood, and 19 articles show statistically significant positive effects (i.e. statistically non-significant positive relationships would indicate that there is less confidence in the findings). The studies dealing with multiple taxa found different significance levels between the taxa (Table 11).

Out of the 12 studies with thresholds[3], 10 thresholds were calculated using the same metric for deadwood volume per hectare (m^3/ha), also in combination with an additional deadwood characteristic, such as decomposition stage, tree height and diameter at breast height (DBH). The 2 remaining studies used the number of dead trees per hectare and the basal area of standing deadwood in m^2 per hectare as their threshold metrics (Table ***9***). On the contrary to threshold results, the studies containing curves without thresholds have more varied metrics. Deadwood volume expressed in m^3/ha is mostly used, some of which include further specifications, but other measurements of deadwood are also common, e.g., deadwood proximity, change in deadwood amount, deadwood structures in m^2, presence of dead material, the summed length of deadwood pieces in m, deadwood isolation, deadwood substrate type and decay stages, volume of stumps, stump extraction intensity, basal area of snags (m^2/ha), and deadwood diversity. The metric for species response also varies from the number of different species to the number of individuals, multi-diversity of all taxa or percentage of recent and old foraging marks (Table 11).

From all articles ranked "1" or "2", approximately 11% were review articles. Half of them limited their search to European ecosystems, one of them specifically Fennoscandia. The remaining articles did not apply any geographical exclusion to their search. Two reviews focused solely on fungi as saproxylic species and one focused only on beetles and fungi for being the only taxa with sufficient information to include in an analysis. The rest of the reviews included all species found in the articles they reviewed. Three review articles highlight that there is a high number of articles available but a very low number of them including suitable and relevant information which can be used in an analysis. The first of these reviews analysed 162 articles but found only 6 reported thresholds for certain forest management, the second review found 152 potentially relevant articles, out of which only 20 could be analysed. The third review found 412 correlations between deadwood and biodiversity, but strong evidence that the indicators in question accurately indicated specific aspects of biodiversity were found for only six. Overall, the reviews highlight that information is not equally available for all taxa, with some of them being underrepresented. Nevertheless, there is a clear link between forest management or silvicultural practices and biodiversity, although significant results are scarce. Even though the correlations between species and deadwood amount are mostly positive, other factors different than deadwood are also important to understand saproxylic species richness (Table 12).

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[3] These are result of the methodology applied for this study, following the criteria explained in Chapter 2. Thresholds included in external literature review did not follow the validation criteria of the present study.

Table 9: Thresholds for deadwood and biodiversity including the species studied and the country in which the research was carried out.

Species	**Threshold and relationship**	**Country**	**Reference**
Three-toed woodpecker	Increase in the probability of three-toed woodpecker occurrence up to a threshold of 44-50 dead trees per hectare, followed by a decrease in the probability of occurrence	Germany	(Zielewska-Büttner, et al., 2018)
Saproxylic beetles*	64 m^3/ha deadwood	Germany	(Müller, et al., 2010)
Saproxylic insects*	The abundance of all saproxylic insect families increased with advancing decomposition, on trees taller than 18 m, and above a living stand volume of 41 m^3/ha	Austria	(Oettel, et al., 2022)
Bryophytes*	60 m^3/ha of lying deadwood with a minimum diameter of 30 cm concerning the overall richness	Austria	(Kropik, et al., 2021)
Cavity nesters (birds)	Greater bird densities in areas with deadwood exceeding 15-20 m^3/ha	Poland	(Bujoczek, et al., 2021)
Fungi*	Threatened species were not found in stands with under 20 m^3/ha of deadwood	Finland	(Penttilä, et al., 2004)
Fungi*	18 m^3/ha is the threshold value established in the study for the occurrence of red-listed species	Finland and Russia	(Ylisirniö, et al., 2012)
Species of conservation concern*	20 m^3/ha of CWD in Northern region, 22,4 m^3/ha in Southern region	Sweden	(Hekkala, et al., 2023)
Three-toed woodpecker*	Almost 1.6 m^2/ha (basal area) of standing deadwood with a DBH >10 cm	Sweden, Switzerland	(Bütler, 2003)
Saproxylic beetles*	Threshold value of 32.04 m^3/ha between species richness and deadwood volume (confidence interval between 16.09 and 64.09 m^3/ha)	Italy	(Della Rocca, et al., 2014)
Bats	Threshold of 24.59 m^3/ha detected only in relationship between standing deadwood and species richness	France	(Tillon, et al., 2016)
Flying saproxylic beetles	70 m^3/ha	France	(Godeau, et al., 2020)

Table 10: Relationship between deadwood and biodiversity from which the thresholds in Table **9** were derived.

Species	Relationship between deadwood and biodiversity	Country	Reference
Three-toed woodpecker	Threshold derived from General Additive Models (GAM)	Germany	(Zielewska-Büttner, et al., 2018)
Saproxylic beetles*	Models estimated by multiple linear regression with deadwood amount (m^3/ha) included as a variable	Germany	(Müller, et al., 2010)
Saproxylic insects*	Multivariate conditional inference tree (CTREE) constructed from variables selected for the final regression model	Austria	(Oettel, et al., 2022)
Bryophytes*	Breakpoints for segmented relationships of the total number of species and the covariate deadwood (m^3/ha)	Austria	(Kropik, et al., 2021)
Cavity nesters (birds)	Relationship between the density of primary and secondary cavity nesters and deadwood volume (m^3/ha)	Poland	(Bujoczek, et al., 2021)
Fungi*	Correlation between the number of species and threatened species, and the volume of dead wood (m^3/ha)	Finland	(Penttilä, et al., 2004)
Fungi*	Observed and predicted values in the generalized additive models for the total number of species and the number of red listed species against the total amount of coarse woody debris (m^3/ha)	Finland and Russia	(Ylisirniö, et al., 2012)
Species of conservation concern*	Richness of species of conservation concern and of red-listed species plotted against deadwood volume (m^3/ha)	Sweden	(Hekkala, et al., 2023)
Three-toed woodpecker*	Relationship between snag diameter and number of woodpecker foraging marks; snag-diameter frequency distribution in forests with and without three-toed woodpeckers; basal area of snags in forests with and without three-toed woodpeckers	Sweden, Switzerland	(Bütler, 2003)
Saproxylic beetles*	Species richness versus dead wood volume (m^3/ha)	Italy	(Della Rocca, et al., 2014)
Bats	Species richness plotted against standing deadwood (m^3/ha)	France	(Tillon, et al., 2016)
Flying saproxylic beetles	Fitted species response as a function of deadwood volume (m^3/ha)	France	(Godeau, et al., 2020)

* Red-listed species or species of conservation concern

Table 11: Studies illustrating a relationship between deadwood and biodiversity including the species studies, a description of the relationship established and the country in which the research was carried out.

Species	Relationship between deadwood and biodiversity	Country	Reference
Saproxylic insects*	Linear model showing the relationship between the predicted number of species and the amount of deadwood (m^3/ha) **Positive significant relationship**	Ten European countries (continental scale) and Germany (regional scale)	(Müller, et al., 2015)
Macroarthropods	Median per 600 cm^2 of the densities of the six most common groups of soil macro-arthropods, comparing sites close to or distant from coarse woody debris. **Positive significant relationship**	Germany	(Jabin, et al., 2004)
Saproxylic beetles*	Species richness of saproxylic beetles or red-listed saproxylic beetles plotted against the volume of standing deadwood (m^3/ha) in disturbed and intact or disturbed and salvaged stands **Positive significant effect of deadwood shaping community composition**	Germany	(Cours, et al., 2021)
Multitaxa (beetles, birds, fungi, plants and true bugs)	For each taxon, species density was plotted against the log-ratio change in deadwood amount [log(m^3_{after}/m^3_{before})]. Multi-diversity of all taxa was plotted against the log-ratio change in deadwood amount [log(m^3_{after}/m^3_{before})]. **Positive significant relationship for saproxylic species (beetles and fungi)**	Germany	(Doerfler, et al., 2018)
Multitaxa (beetles, fungi, plants, birds)	Functional-phylogenetic diversity plotted against the change deadwood amount [log(m^3_{after}/m^3_{before})] **Positive significant effect for beetles**	Germany	(Doerfler, et al., 2020)
Bees	Wild bee species richness in relation to deadwood structures (m^2) **Positive significant relationship for n° of species**	Germany	(Felderhoff, et al., 2022)
Birds	Observation frequency of forest birds up to 25 meters around groups of dead material, or large individual dead trees	Germany	(Utschick, 1991)
Gastropoda, isopoda, diplopoda	Effect of the volume of coarse woody debris on the difference between the multivariate dispersion indices of samples taken close to coarse woody debris and distant from coarse woody debris **Positive significant relationship for faunal heterogeneity of shelled Gastropoda**	Slovakia and Germany	(Kappes, et al., 2009)
Beetles	Species accumulation curves derived for coarse woody debris sites (number of species against cumulative number of samples) **Positive significant influence of CWD on the number of species and individuals**	Slovakia	(Topp, et al., 2006)
Fungi*	Alpha diversity of red-listed species against total deadwood volume (m^3/ha) **Positive significant effect of total deadwood volume on alpha diversity**	Slovakia	(Ferenčík, et al., 2022)
Multitaxa (beetles, fungi, bryophytes, lichens)	Effect of deadwood amount (summed length of dead wood pieces in meters) and isolation (median distance of dead wood pieces to the plot center) along their gradients on changes in community composition **Positive significant relationships between dead wood amount and species richness**	Switzerland	(Haeler, et al., 2021)
Saproxylic beetles*	Mean number of individuals against deadwood (m^3/ha within 4 and 1 km^2) **Positive significance for species richness**	Norway	(Økland, et al., 1996)
Fungi*	Sample-based species accumulation curve and individual-based rarefaction curve for total fungal species richness in relation to deadwood substrate type and in relation to decay stages of deadwood **Small but positive significant impact on species richness**	Denmark	(Atrena, et al., 2020)

Beetles	Linear relationship between the volume of stumps and the abundance of saproxylic beetles	Sweden	(Geijer, et al., 2014)
Beetles*	Number of individuals per m^2 plotted against the stump extraction intensity in the landscape (%)	Sweden	(Ranlund & Victorsson, 2017)
Fungi*	Observed and predicted values for (a) the total number of species and (b) number of red-listed species plotted against total coarse woody debris (m^3/ha)	Russia and Finland	(Ylisirniö, et al., 2012)
Woodpecker species*	Relationship between the occurrence of four woodpeckers and the basal area of coniferous/deciduous snags (m^2/ha) **Positive effect but not significant in Lithuania**	Sweden, Lithuania, and Poland	(Roberge, et al., 2008)
Fungi	Relationship between polypore species-richness in 2 ha plots and the amount of downed coarse woody debris (m^3/ha) **Positive significant effect**	Estonia	(Runnel & Löhmus, 2017)
Saproxylic beetles	Linear regression of saproxylic beetle species richness against volume and diversity of deadwood **Positive significant effect**	France	(Brin, et al., 2009)
Saproxylic beetles	(1) Prediction of the response of species abundances to the environmental variable "Deadwood" (volume (m^3) of lying deadwood (>7 cm in perimeter) per hectare) and (2) Prediction of the response of species diversity to the environmental variable "Deadwood" (volume (m^3) of lying deadwood (>7 cm in perimeter) per hectare)	Spain	(Micó, et al., 2022)
Saproxylic beetles*	Species response to dead wood volume (m^3)	Poland	(Jaworski, et al., 2019)
Amphibians	Relationship between median amphibian abundance per plot and deadwood volume (m^3) **Significant positive effect for old growth forests**	Poland	(Pabijan, et al., 2023)
Longhorn beetles*	Relationship between the number of species and individuals and deadwood volume (m^3) **Positive significant relationship**	Poland	(Karpiński, et al., 2021)
Fungi	Relationship between macrofungal diversity and the 2nd and 3rd decay stage of downed coarse woody debris (m^3) **Positive significant relationship**	Romania	(Copot & Tănase, 2019)
Beetles	Species accumulation curves for coarse woody debris and fine woody debris in different decay stages	USA	(Ferro, et al., 2012)
Black-backed woodpecker	(1) Influence of the percentage of early-decay snags in relation to the percentage of recent foraging marks and (2) basal area of trees (m^2/ha) in relation to the proportion of old foraging marks	Canada	(Martin, et al., 2021)
Beetles	(1) Relationship between intermediate-sized deadwood volume and total richness in hardwood stands and (2) relationship between well-decayed deadwood volume and total richness in softwood stands **Positive significant relationship**	Canada	(Kehler, et al., 2004)
Bryophytes	Epixylic richness as a function of mean deadwood decomposition class and mean deadwood diameter	Canada	(Arseneault, et al., 2012)

* Red-listed species or species of conservation concern

Table 12: Highly ranked review articles found during literature review with regions and species included and conclusions of the studies

Regions covered	Species covered	Conclusions	Reference
European beech forests	Plants, lichens, fungi, beetles, snails, birds, other arthropods	• Authors had relatively firm knowledge regarding the most important habitat qualities on which major species groups depend on in European beech forests. • So far, the studies available on thresholds indicate that only beech forests with trees that are at least 180 years old and that have accumulated volumes of 20 m^3/ha CWD or more contain rich assemblages of specialized epiphytic and saproxylic species.	(Brunet, et al., 2010)
European forest ecosystems	Amphibians, arthropods, birds, fungi, mammals, plants, reptilians	• Biodiversity in European forests is linked to silvicultural management measures. • High structural diversity is linked to high levels of biodiversity • Most appropriate indicator species or groups are those which: (1) have a strong link to a management indicator, (2) are sensitive to changes, and (3) are not related to similar habitat needs to cover different gradients of management influences • Out of 162 studies, only 6 thresholds for forest management were reported • The links between the abundance of deadwood and saproxylic species or between stand structure and birds are very well established, while other taxonomic groups are underrepresented.	(Oettel & Lapin, 2021)
No exclusion of regions	Plants, animals, fungi	• Species richness tended to be higher in unmanaged than in managed forests, but the response varied widely among taxonomic groups • The effect of forest management varied with management intensity • Number of studies suitable for meta-analysis proved much smaller than expected • Forest conservation priority should focus on saproxylic beetles, bryophytes, lichens, carabids, and fungi because these taxa proved the most sensitive to forest management. Nevertheless, other taxonomic groups also need to be monitored because there were few studies available on these groups for our meta-analysis. More generally, because different taxa responded differently to forest management, the conservation priority should be taxa whose habitats are most threatened by forest management (e.g., dead wood, infrequently disturbed areas).	(Paillet, et al., 2009)
No exclusion of regions	Beetles, fungi	• Positive but weak relationship between total deadwood volume and saproxylic species richness: the volume of deadwood is not the only factor driving saproxylic species richness • This systematic review of the literature revealed that the papers eligible for meta-analysis were less numerous than we first supposed: out of 152 potentially relevant articles, only 20 could be analysed. • In terms of forest management, the significant positive correlations suggest that any forest practices enhancing deadwood increment at the local scale would benefit saproxylic biodiversity (notably in boreal forests).	(Lassauce, et al., 2011)
Europe	Birds, mammals, reptiles, invertebrates, plants, lichens, fungi	• The review demonstrated that no species/compositional indicator had strong evidence of a correlation. However, these indicator relationships are poorly understood and rarely substantiated across habitats, scales etc.	(Gao, et al., 2015)

		• Of the 412 correlations, strong evidence that the indicators in question accurately indicated specific aspects of biodiversity were found for only six, and all of these were related to four structural indicators (deadwood). • The results revealed that there was strong evidence only for deadwood volume and diversity as indicators of saproxylic beetle and fungal species and extrapolating this relationship to other elements of biodiversity could be, as most projects did, misleading. Our results also revealed that individual biodiversity indicators normally only indicate a narrow spectrum of biodiversity. Multiple indicators need to be applied if a wider spectrum of biodiversity is to be described.	
No exclusion of regions	Beetles, other arthropods, birds, reptiles, fungi, lichens	• Author's stand-scale meta-analyses showed a consistent positive effect of deadwood enrichment on the abundance and species richness of saproxylic insects in coniferous forests, but in mixed forests the response was not significant. • The review suggests that manipulating deadwood can be an effective part of conservation management to support biodiversity in protected forests. • The included studies were strongly dominated by short-term investigations. What is short-term is context dependent but given the decadal timescale of tree decomposition, this is an unfortunate bias in the evidence base.	(Sandström, et al., 2019)
Europe	Birds, beetles, fungi, other invertebrates	• Thresholds vary among studies with different species, and in different regions and habitats, and the most-demanding species require amounts of dead wood that are virtually impossible to reach in managed forests. • Yet it was demonstrated that a similar peak of threshold values can be found for the three main types of Central European forests (lowland beech–oak forests, mixed-montane forests, and alpine-boreal montane forests) at 20–50 m^3/ha, ranging from 20 to 70 m^3/ha when most values are included	(Müller & Bütler, 2010)
Fennoscandia	Fungi	• First, there seems to be thresholds for the minimum patch size, amount of dead wood and tree diameter at the stand scale. We thereby suggest a heuristic 20/20/20 rule of thumb for boreal spruce forests: an area of at least 20–30 ha, with a minimum volume of 20–40 m^3 of dead wood per hectare is likely to harbour a species-rich polypore assemblage if most of the dead wood are logs with at least 20–30 cm diameter. • Both the current and the historic extent of suitable habitat at the landscape scale are crucial for polypore persistence.	(Junninen & Komonen, 2011)
No exclusion of regions	Fungi	• Silvicultural practices, by modifying stand characteristics and microclimatic conditions, may have different effects on fungal communities according to the type of treatments, the methodological approaches and the target functional groups investigated. • Abundance and diversity (in size and decomposition stage) of deadwood are reported as features positively related to richness of wood-inhabiting fungi.	(Tomao, et al., 2020)

As no thresholds were found for the United Kingdom during AFRY's literature research, an additional threshold for Great Britain was included from the review article of Müller and Bütler (2010) (Table 13) (Müller & Bütler, 2010). The origin of the threshold is explained in the original article: *"The following, based on the range of values found in this survey, are proposed as provisional benchmarks for amounts of dead wood in British broadleaved forests: low <20 m³/ha lying dead wood, 0-10 snags/ha (all below 10 cm diameter); medium 20-40 m³/ha lying dead wood, 11-50 snags/ha (of which some are more than 10 cm diameter); high >40m³/ha lying dead wood, more than 50 snags/ha (of which some are more than 40 cm diameter)"* (Kirby, et al., 1998).

Table 13: Additional deadwood threshold for Great Britain *(Müller & Bütler, 2010)*

Species	Threshold	Country or area	Reference
Saproxylic organisms	20-40 m^3/ha medium (lying only); >40 high (lying only)	Great Britain	(Kirby, et al., 1998)

3.2 Deadwood records and deadwood guidelines in Europe

To identify existing limiting factors impacting wood residue removals by country, records of deadwood volumes and types were searched for in the National Inventories as well as guidelines on deadwood retention[4] in the forest and on biodiversity. Table 14 summarises the results of these consultations, from the countries where thresholds have been found as result of the literature review. A more detailed description of each country's existing guidelines follows the table.

Table 14: Summary of countries with deadwood records in the National Forest Inventories

Country	Deadwood records	Threshold recommended	Existing deadwood regulation guidelines
Germany	Yes	Yes	Yes
Austria	Yes	Yes	Yes
Switzerland	Yes	Yes	Yes
Sweden	Yes	Yes	Yes
Finland	Yes	Yes	Yes
Poland	Yes	No	No
United Kingdom	Yes	Yes	Yes
France	Yes	No	Yes
Italy	Yes	No	Yes

Germany

The Third Federal Forest Inventory is the most recent national publication, which contains information on deadwood from the observation period 2002-2012. The federal forest inventory is a terrestrial sample with permanent sample points. Inventory teams always record data at the same sample points at each subsequent inventory. This is done in all states and in all ownership types according to a uniform procedure every 10 years. This procedure was already established in the 1980s, when the founders of the Federal Forest Inventory started using a four-by-four-kilometer grid across the entire country, which has been subsequently used for every inventory. At the corners of each grid cell (side length of 150 m) is where sampling takes place (Bundeswaldinventur, 2012).

The amount of deadwood increased from 2002 to 2012 by 18%. On average there is 20.6 m^3/ha and a total of 224 million m^3 across the country, which accounts for 6% of the amount of living trees. Almost half of the deadwood (49%) is lying deadwood, 23% is standing deadwood and 28% are rootstocks. Around half of the deadwood is in an advanced decomposition stage or heavily decayed and most deadwood pieces are larger than 30 cm in

[4] Retention: the continued use, existence, or possession of something or someone (Cambridge Dictionary)

diameter. The information on deadwood volumes can be obtained for each state and type of deadwood, type of forest ownership, decomposition stage or tree family (Bundeswaldinventur, 2012).

The Federal Nature Conservation Act was screened for deadwood-related policies. § Section 5 (3) includes the following clause: *"In the commercial use of the forest, the aim is to establish near-natural forests and to manage them sustainably without clear-cutting. A sufficient proportion of native forest plants is to be maintained"* (Bundesministerium der Justiz, 2009). The state Nordrhein Westfalen has a supplementary statement in its State Nature Conservation Act, which builds upon the Federal Conservation Act and specifies *"commercial use of the forest shall pursue the goal of leaving standing thick-stemmed deadwood of deciduous trees in the forest. To implement this objective, the ministry responsible for nature conservation and forestry may conclude a framework agreement with the forest owners' associations"* (Ministerium des Innern des Landes Nordrhein-Westfalen, 2023). Additionally, each German state has its own laws regarding forest management. In Bavaria, deadwood eligible for being untouched includes "*standing deadwood with a DBH of at least 40 cm, lying deadwood with a diameter of at least 40 cm at the stronger end and a minimum length of 3 m, and all native tree species except spruce*" (Bayerische Staatsministerien für Umwelt und Gesundheit sowie für Ernährung, Landwirtschaft und Forsten, 2010). Nevertheless, other states are rather broad and unspecific regarding deadwood requirements. Baden-Württemberg only mentions deadwood in its State Forest Act in the following clause: *"[…] Sufficient habitats for native flora and fauna are to be preserved, for example by leaving dead wood; the requirements for maintaining a healthy and appropriate game population are to be taken into account"* (Landesrecht BW, 2023). Generally, the Third Federal Forest Inventory recommends keeping 1 m^3 of wood per hectare annually to maintain a permanent deadwood supply of 20 m^3/ha (Bundeswaldinventur, 2012).

Austria

In total, the Austrian Forestry Inventory sampling network comprises around 11,000 sample plots in the forest. Every year since 2016, seven survey teams have been active throughout the country to carry out the extensive measurements on the sample plots. Around 200 forest and environmentally relevant parameters are recorded (Bundesforschungszentrum für Wald, 2022).

Information on deadwood can be obtained for the period 2016-2021. Information on each region of the country is available for standing deadwood and the different forest management types. For the entire country, information is available for standing deadwood and type of forest ownership as well as for type of forest regarding the trees present. The records show Austria has a total deadwood amount of 9.7 m^3/ha, and the region of Vienna has the highest deadwood stocks per hectare with 20.8 m^3/ha (Bundesforschungszentrum für Wald, 2022).

No official State Nature Conservation Act that included deadwood specifications was found for Austria. However, the Federal Forestry has published the Nature Conservation Practical Book, which includes nature conservation measures as a contribution to ecological landscape management. In it, deadwood is briefly mentioned and stated that the Austrian Federal Forestry has agreed on a target value of 25 m^3/ha of deadwood for commercial forests (Österreichische Bundesforste AG, 2017).

Switzerland

The National Forest Inventory (NFI) is designed as a sample inventory. A part of the Swiss forest is randomly selected and recorded in detail. The sample areas of the NFI are located on the intersections of grids, which cover the whole area of the country (systematic sampling). The Fourth National Forestry inventory was conducted using grid cells of 1,4 km in length. Of the total of 20,638 intersections of the base network, 6,617 were in forests (Brändli, et al., 2020).

According to the Fourth National Forest Inventory (2009-2017), Switzerland has 24.2 m^3/ha of deadwood in its forest, with Voralpen and Alpen being the regions with the highest deadwood densities (31.2 m^3/ha and 30.0 m^3/ha respectively). Further information on deadwood volumes is recorded, according to potential natural vegetation and priority function, by main tree species and elevation, by tree condition, diameter, wood strength, the comparison between coniferous and deciduous trees and the comparison with past inventories. Since the Second National Forest Inventory, the volume of deadwood has increased by 138%, partly as a result of the Hurricane Lothar in 1999. The quality of deadwood has also improved since the Third National Forest Inventory: the proportion of thicker diameter deadwood and more decomposed deadwood has increased (Brändli, et al., 2020).

The Federal Office for the Environment has published different documents related to nature conservation and forest management that mention deadwood. The Forest Policy 2020 includes a target value of 20 m^3/ha for the regions of Jura, Mittelland and Alpensüdseite and a target value of 25 m^3/ha for the regions of Voralpen and Alpen (Bundesamt für Umwelt, 2011). The Biodiversity Strategy of Switzerland includes deadwood in the context of forest management: "*The legally anchored near-natural silviculture will be implemented on the entire managed forest area. The area of forest reserves is to be increased from 5 to 8 % of the total forest area. Deadwood and diverse structures should be present - in ecologically sufficient quantity and quality - in all large regions of Switzerland. Where habitat protection is not sufficient, specific species promotion measures should protect and promote forest-bound species."* (Bundesamt für Umwelt, 2012). Lastly, the communication on the amendment of the Federal Act on Forests and on the popular initiative "Save the Swiss Forest" enhances that "*[…] sufficient proportions of deadwood and biotope trees (trees which, due to their type or nature, are of special importance for fauna and flora) shall be left. In areas important for breeding and rearing of rare and endangered animals, appropriate rest periods shall be ensured during which no timber exploitation takes place*." (Bundesamt für Umwelt, 2007).

Sweden

Deadwood has been included in the Swedish inventories since 1994. Therefore, there is a large body of data already collected. Deadwood observations are limited dimensionally by the following factors:

- >10 cm in basal diameter
- >1.3 m in length

The characteristics of deadwood were captured by defining:

- decay stages from 1 to 4 (1 - <10% of the wood decayed; 2 - 10–25% of the wood decayed; 3- 26–75% of the wood decayed; 4 - 76–100% of the wood decayed)
- tree species
- position as standing or laying

The observed deadwood has increased by 25% through the 15-year period across the Swedish forests except for the most northern region (Jonsson, et al., 2016). Jonsson et al., (2016), show that the largest increases of the dead wood were correlated to the storms passing Sweden and a minor part of increase was attributed to the policies in place. The average observed volume of deadwood was 6.08 m^3/ha and 7.6 m^3/ha for managed forests.

Lying deadwood was more prevalent and accounted for 60% of all volume but standing wood proportion has grown since 1994 from 30% to 40%. However, in the west of the country the increase was not observed and the proportion of standing dead trees stayed stable. The comparison of the last two NFI periods indicate that deadwood accumulation slowed down and a stable amount could be soon reached.

The deadwood volume was predominantly comprised by conifers, while temperate broadleaves appeared only in the southern regions. Spruce deadwood has increased in the southern regions, while pine deadwood reduction was observed in the north during the investigation period.

Forest age had a strong influence on deadwood amount with lowest amounts in the young stands and the maximum >14 m^3/ha was reached in the oldest age group (>150 years). Lastly, the observed tree diameter showed that deadwood volumes were dominated by small diameter trees (<20 cm) in all regions. This pattern was consistent among all the species, with only 10% of dead tree being >30 cm in diameter.

The Forestry Act is the major law legislating forest use in Sweden, while voluntary forest certification schemes are highly adopted and extend influence through standard requirements (Johansson, et al., 2013). Both Forestry Act and the certification schemes stress the importance of deadwood for forest biodiversity. FSC standard require retention of already existing deadwood and leaving at least three high stumps or girdled trees after the final harvest in each harvested forest hectare (FSC, 2019). Additionally, Swedish government endorsed a set of environmental objectives in 2000 (Swedish Ministry of Environment, 2001), which specified that wood that is decayed <10% (stage 1) should increase by 40% in whole Sweden. The Swedish Forest agency provides guidance and best practices to forest owners (Skogsstyrelsen, 2022). The agency advises that all deadwood found during forest operation should be left in the forest and not damaged. However, stump and harvesting residue collection is allowed. The only restriction is related to compensating for nutrient deficiencies due to these operations.

Finland

The latest Finnish NFI was carried out 2014-2018 (Korhonen, et al., 2021). Similarly, to Swedish NFI the observations on deadwood were confined by accounting for:

- tree position (standing and lying)
- diameter >10 cm in diameter and length more than 1.3 meters
- decay classes 1-5 that correspond to visual verification and testing decay depth with a knife: 1 – Bark mostly firmly attached, most branches remaining; 2 – Branches are falling, bark of conifers beginning getting loose; 3 – Conifers have lost the bark, except for lower parts. Deciduous trees bark remaining but wood softening; 4 – No bark, covered by epiphytes, large lichen and moss vegetation; 5 – Very soft, easy to break with fingers.

In Finland forestry operations are allowed on productive or poorly productive land. On average deadwood volume in these two types of forest and on land that is allowed to be under active management (managed forests) were 4.3 m^3/ha and 4.1 for m^3/ha respectively for productive and poorly productive forests. Most deadwood was in the northern productive forests of 7.5 m^3/ha, while in the southern were 4.4 m^3/ha. Comparing 1996-2003 NFI with the latest 2014-2018 NFI there was a clear decrease of deadwood in the North and increase in the south of Finland. However, the amount of deadwood was stable between the inventories when whole country is evaluated at an average of 5.7–5.9 m^3/ha.

The proportion of standing wood was about 30%, with no large changes between the 1996-2003 NFI and 2014-2018 NFI. Forest age class had similar influence as in the other Nordic countries, most deadwood – 9.7 m^3/ha was accumulated in the oldest - mature stands. Lastly, the proportion of >30 cm deadwood is 19% of the total volume of deadwood.

The Forest Act in Finland provides general guidance about valuable habitats and their preservation, but productive forests on stable soils without special natural features can be managed with relative freedom (Ministry of Agriculture and Forestry, 2014). In the Finnish forest management recommendations, there is no retention tree requirement (Äijäla, et al., 2019). A threshold of 20 m^3/ha is mentioned as a prerequisite for rare species to appear. If harvesting residues are removed the recommendation is to leave about 30% on site. Stump harvesting is allowed, but it is recommended to leave 25 stumps per ha. The most prevalent standard for voluntary forest certification is PEFC and it requires to leave 10 retention and 10 dead trees in the harvesting site per hectare (PEFC, 2022). The dead trees are limited to >20 cm diameter and can be snags or other standing or lying deadwood. FSC standard is gaining popularity in Finland and has been promoted by the major forest industry companies. New FSC national standard will come into effect in August this year (FSC, 2022). The required amount of retention trees is the same as in PEFC standard, but more specific requirements are applied to dead trees. All the dead trees that are >10 cm diameter must be retained, unless the Forest Damages Prevention Act requires their removal. Only where freshly formed (decay class 1) deadwood exceeds 20 m^3 per hectare on the site the exceeding amount can be removed.

Poland

The Forest Act of 28 September 1991, (Journal of Laws, 2017, item 788) legally obliged the State Forests to publish an annual report on the condition of forests in Poland. The scope of the annual report covers three main issues: forest resources in Poland, forests functions, and threats to the forest environment. As part of the National Forest Inventory (NFI), Poland is covered with a 4 × 4 km grid of sample plots based on the 16 × 16 km ICP Forests network used in the European Union to evaluate forest damage. Depending on the age of the dominant tree species, the sample plots range in size from 200 to 500 m^2. Conservation objectives defined for the Natura 2000 network, have motivated studies in Poland for accounting deadwood volume and the density of large deadwood pieces used for evaluating the quality of forest habitat types designated under the Habitats. Deadwood was last assessed in Poland in 2015 for the State of Europe's Forests 2015, published by the FAO and the European Forest Institute (EFI) (Forest Europe, 2015).

As part of the Habitats Directive (Natura 2000) the countries participating in the Natura 2000 network are required to monitor the conservation status of the natural habitats and species listed in its appendixes (European Commission, 1992).

The removal of dead and dying trees is perceived as detrimental to most forest habitats and is being monitored on Natura 2000 sites. The adoption of an appropriate deadwood management strategy requires knowledge about the ecology of saproxylic organisms, including the size and dispersal of their populations.

Poland does not have a specific biodiversity guideline in place with regards to deadwood conservation in the forest. There are manuals referring to habitat evaluation in Poland (Bujoczek, et al., 2021). In most cases, a favourable conservation status requires a deadwood volume of >20 m^3/ha and a density of at least 3–5 large deadwood pieces per hectare; large pieces are understood as those having a diameter/DBH of >50 cm (or in some cases >30 cm) and a length/height of >3 m.

Particularly problematic is the scarcity of large deadwood. Therefore, in managed forests fragments of saw timber stands should be left to die naturally and decay. Further monitoring is necessary as the evaluation of the Natura 2000 network depends both on its duration in individual Member States and on the adopted conservation principles for the included areas.

The average deadwood volume reported for all Polish forests is 5.9 m^3/ha (Bureau for Forest Management, 2014).

United Kingdom - Great Britain

The National Forest Inventory in the United Kingdom (NFI UK) records three types of deadwoods: standing dead trees, lying deadwood and stumps. The NFI UK Deadwood Calculator derives a standing deadwood volume per hectare, a lying deadwood volume per hectare and a stump volume per hectare. The methodology is set out in a document available on request from the NFI UK. The NFI UK Condition Calculator uses the deadwood volume from standing dead trees and lying deadwood only, to match the UK Forestry Standard (Forestry Commission, 2017). The NFI UK records the volume of deadwood (m^3 per hectare) in woodland stands in Great Britain by habitat type.

There are several specific statutory and non-statutory requirements relating to biodiversity, wildlife protection and conservation that have a bearing on the management of deadwood. The UK Forestry Standard (Forestry Commission, 2017) and the UK Woodland Assurance Standard (UKWAS, 2018) both emphasise the need to take account of deadwood when seeking to attain standards of sustainable management.

References provided by the UK Forestry Commissions refers to a volume of deadwood of 20 m^3/ha (not including stumps, which are usually retained after felling) should be present across the forest management unit (FMU). Implementing a differential approach to deadwood management should ensure that deadwood is not uniformly distributed across the FMU and effort is focused where it is most needed.

This approach requires that areas of high ecological value be identified during management planning and are classified into low, medium, and high value according to 5 factors (current levels of deadwood on site; continuity and diversity of deadwood habitats over time; known interest for species associated with deadwood; ecological connectivity and history of management).

The guideline "Managing deadwood in forests and woodland" has been written for woodland owners and managers to help improve forest condition and fulfil objectives for sustainable forest management and the UK Biodiversity Action Plan, and as implementation of the guidelines for managing deadwood set out in the UK Forestry Standard (UKFS) "Guidelines on Forests and biodiversity" (Humphrey & Bailey, 2012).

In more than 50% of the forest the volume of deadwood recorded lies between 0 and 10m^3/ha, most of the area belonging to non-native coniferous woodland and lowland mixed deciduous woodland (Forest Research, 2023).

France

Since 2008, the national forest inventory quantifies the deadwood present in the forest for both standing and lying deadwood. The most recent data is from 2021, providing results broken down by type of deadwood. The inventory of lying deadwood has been carried out since 2008 based on sampling with a 12-metre-long transect centered on the inventory point, with a random azimuth. It includes (i) residues of branches or shaped wood scattered on a cutting bed dating back more than one year, (ii) residues from pruning or forestry operations, not considered as harvesting residues, regardless of the date of the operation and (iii) lying branches of a crown, following an operation more than one year old, or following a natural disturbance. Between 2008 and 2014, windfall trees showing no signs of life are counted as deadwood when they fall on the transect. From 2015: windfall trees, living or dead falling on the transect, are no longer counted in lying deadwood (which leads to a break in the series of lying deadwood) (IGN, 2012).

The average deadwood volume and its 95% confidence interval are calculated for each of these three categories of wood, for each region, in 2008-2012 and 2013-2017. By simulating data according to these means and confidence intervals, the geometric mean of these volumes is calculated for each period, taking the average first on the types of wood and then on the region. The final metric is a summary (mean and confidence interval) of these simulated geometric means divided by the mean of the simulated geometric means for the reference period. The geometric mean has the property of being less sensitive to extreme and strong values than the arithmetic mean. No data of deadwood per ha is provided and no guidelines on deadwood permanence in the forest for the biodiversity preservation are published (IGN, 2012).

Italy

The Third Italian National Inventory of Forests and Forest Carbon Sinks (2015) includes data on deadwood amounts, divided into lying deadwood, standing dead trees and stumps. Standing dead trees amount to 67.3 million m^3, 7.4 m^3/ha on average. Lying deadwood is the second component in forests, with a total value of 51.8 million m^3, 5.7 m^3/ha on average. Stumps are 783.8 million in numbers (86.3 per hectare on average) for a total volume of 14.0 million m^3 (1.5 m^3/ha) (Gasparini, et al., 2022).

To be included in the inventory, standing dead trees had to have a DBH of >4.5 cm, lying deadwood had to have a diameter and length of >9.5 cm and stumps were the remains of trees not reaching a height of 1.30 m and with a diameter of >10 cm. The design of the Italian NFI is based on a 1 km×1 km grid in which the national territory is divided. These cells are then classified by land cover, land use, and forest types (Gasparini, et al., 2022).

National legislation includes a section on "Orientation and modernisation of the forestry sector", which plans on "*encouraging the release of trees for indefinite ageing in the forest for the conservation of biodiversity […] with particular reference to the preservation of species dependent on woody necromasses*". In Special Protected Areas (SPAs) characterised by the presence of alpine forest environments and SPAs characterised by the presence of Mediterranean mountain forest environments, there is an obligation to integrate forest management tools to guarantee the maintenance of an adequate presence of dead, perennial or decaying plants, useful for nesting or for bird feeding. In SPAs characterised by the presence of mixed Mediterranean environments it is encouraged to maintain an adequate presence of dead, decaying or perishing plants that are useful for nesting or for bird feeding (Dondini, et al., 2008).

3.3 Forest residues availability and collection

Forest woody material, either as standing dead trees or as primary harvesting residues left in the forest will contribute to the amount of deadwood creation. Assessing the volume availability of forest residues will indicate on one hand potential future deadwood volumes in the forest and on the other hand, if large volumes of forest residues are available, the potential available volume to be removed without a large impact on the creation of deadwood and potentially on the biodiversity levels.

Based on the list of countries included in Table ***9***, official wood removals including harvesting residues were consulted. These volumes are indicators of residue availability after the correspondent wood assortments are collected for the industry and if not collected, volumes that otherwise would be left in the forest for decay. Moreover, guidelines in place suggesting trees retention and harvesting residues retention for the purpose of deadwood creation were consulted for each country. Both the information about harvesting residues volumes and deadwood creation national guidelines will allow to identify the most favourable countries for harvesting residues collection where deadwood and forest biodiversity awareness and conservation are in place.

Additionally, the existence of official forecast models allows the prediction of harvesting volumes over the years and facilitates the estimation of supply volumes for biofuel production. This information has been considered as being relevant for the countries investigated and therefore included as a selection criterion and summarised in the table below (Table 15). Sections below include relevant information for the countries where all criteria from the table are met.

Table 15: Countries recording harvesting residues, presenting retention guidelines, and harvesting volume forecast models

Country	Harvesting residues from official national sources	Retention volume in the forest for deadwood creation	Existing official models of harvesting forecast
Sweden	Yes	Yes	Yes
Finland	Yes	Yes	Yes
United Kingdom	No	No	Yes
France	No	No	Yes
Germany	Yes	Yes	Yes
Austria	Yes	No	No
Switzerland	Yes	No	Yes
Italy	No	No	No
Poland	No	No	No

Sweden

The Swedish National Forest Inventory (Swedish University of Agricultural Sciences) records areas and proportion of harvested area with removal of tops and branches in final felling and thinning by Year on a 5-year average. It is believed that largest volumes of harvesting residues and deadwood retention result from clearcut operations. According to the Swedish Forest Agency's annual statistics for 2019, the average Swedish clearcut measures 3.6 hectares. Clearcuts in southern Sweden are generally smaller than those in the northern parts of the country. Groups of trees are left unfelled to protect many different species and to make the harvested area less bare. They provide an important place of refuge for species as the new forest grows. Stumps that measure 2–4 metres in height are left in the forest. In a certified forest, at least 10 trees per hectare are left on the felled area and there are rules that determine how large an area can be left without any trees at all. Lying Trees and wood are also left to decay slowly and create habitats for different insects, larvae, lichens, mosses, fungi etc., that are dependent on wood in varying stages of decay. In the spruce forest it is allowed to take up to 70% of the harvesting residues in 50% of the harvested stands on a landscape level, while in pine and broadleaved forests it is recommended to take limited amounts (Drott, et al., 2019).

The Swedish Forestry Agency makes forest impact analyses (SKA) in collaboration with Swedish University of Agricultural Sciences. In the analyses, several scenarios are developed where Sweden's forests are used and managed in different ways and then calculate what consequences this will have over a 100-year period. The latest forestry impact assessment was presented in October 2022 and is called SKA 22.

Finland

In Finland, forestry generally involves the management of small forest stands where trees are of a similar age. Such stands are managed according to a regeneration cycle extending from planting or natural regeneration to the final harvesting phase, and the length of the regeneration cycle can be between 50 and 120 years, depending on the tree species and the location of a forest stand. Younger commercially managed forests are typically thinned out periodically, with some 25−30 per cent of the trees removed during thinning.

Finnish forests are managed to promote their biodiversity. Ecologically valuable trees including dead and decaying trees are left in the forest during logging, and care is taken to preserve valuable natural features including the habitats of endangered species. Finnish official guidelines recommend leaving around 1/3 of the harvesting volume from a clearcut in the forest as retention volumes for deadwood creation but not exceed 50% of the growing stock (Koivula and Vanha-Majamaa 2020).

Natural Resources Institute Finland publishes data on fuelwood and harvesting residues every year. Sustainable harvesting volumes are modelled and presented on a 10-year basis.

Germany

Statistisches Bundesamt publishes on a yearly basis harvested volumes of wood dedicated to bioenergy and fuelwood and harvested areas.

The 2012 National Forest Inventory (BWI) formed the basis for the Forest development and timber supply modelling (WEHAM: forest development and timber production modelling), which represents an important decision-making aid for the design of forest-related policy programs, such as forest, climate, and nature conservation policies and for planning future forest use. The model considers the demand for wood in the construction, furniture, packaging, paper and energy (Forst Praxis, 2017).

The effects of different forest treatment variants on the forest structure and the future volume of raw wood were calculated with WEHAM. The WEHAM base scenario, which reflects the future forest management currently planned in Germany, was developed by the federal and state governments together with associations. It takes up the current owners' goals of forest management, current and expected market conditions and the existing legal requirements - such as protection area requirements.

In the run-up to the BWI 2012, stakeholders from politics, administration, associations and business have already requested participation in the development of further WEHAM scenarios in order to show and evaluate alternative forest treatment and wood use.

As stated in previous sections, the Third Federal Forest Inventory recommends keeping 1 m^3 of wood per hectare annually to maintain a permanent deadwood supply of 20 m^3/ha (Bundeswaldinventur, 2012).

Industry demand

Large volumes and regular creation of woody residues and deadwood in the forest is to a large extent a consequence of the forest operations taking place in the countries of analysis.

Forest management in Europe is predominantly driven by sawlog production, where large diameter trees are harvested, and crown and branches result as residues from the operations. Main consumers of these residues and thin diameter wood are pulp mills. Residues from crown and branches will be consumed by wood-based panel industries and biomass plants. For this study, the most important driver considered for the largest producer of residue generation and potential creation of deadwood to the expected conservation levels is the sawmilling industry. The harvesting operations aiming to supply the sawmilling industry with high diameter logs and pulp and paper industry with smaller diameter logs generate harvesting residues and hence roundwood harvesting is a necessary pre-condition for harvesting residue supply and mobilization.

The following map presents the location of the sawmills in the countries in Europe included in the scope of this project by size.

Highest concentration of sawmills occurs in Sweden, Finland, Germany, Austria, and Switzerland (Figure 4).

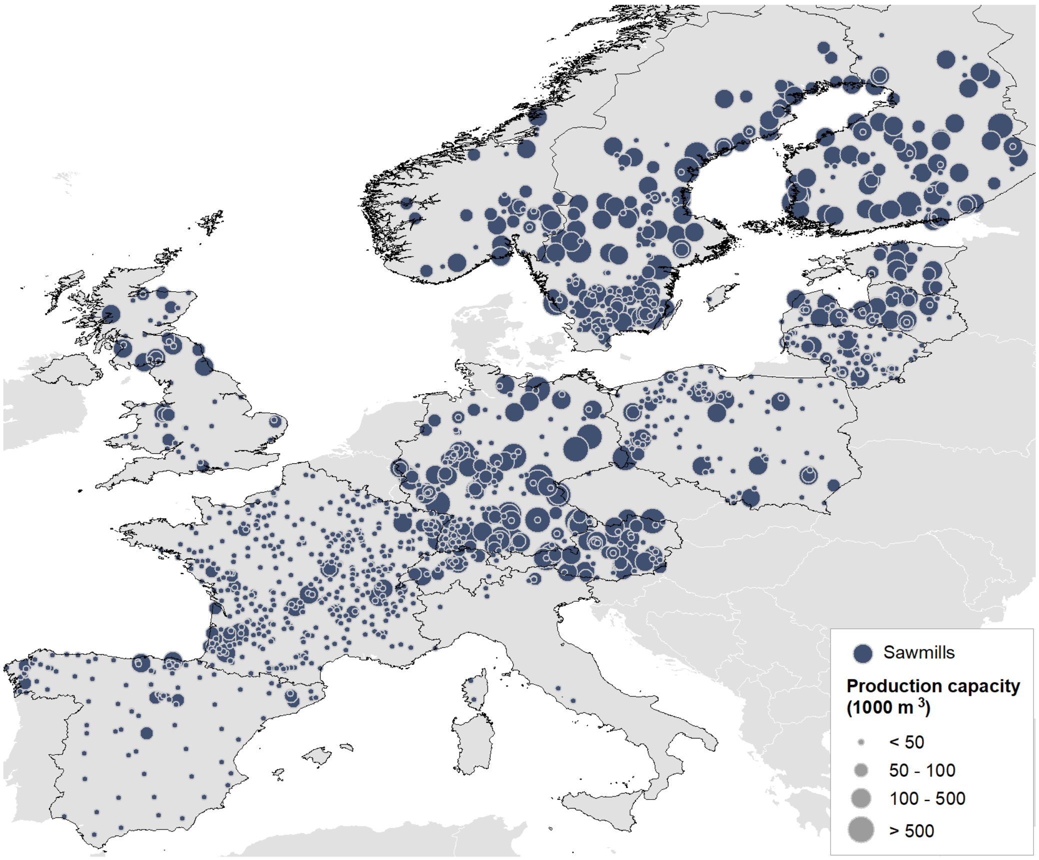

Figure 4: *Location of sawmills in the countries studied in Europe*

4 Quantitative and qualitative analysis of data

This chapter covers the discussion on the type of data included in the studies from the literature review, concerning the impact of deadwood levels on biodiversity. The discussion relates to the challenges associated with the diverse methodological approaches applied to calculate deadwood thresholds and the wide variability associated to them. Furthermore, the discussion addresses the limitations in assessing biodiversity due to the specificity of thresholds to certain species and forest habitats. It also highlights the countries for which deadwood thresholds have been documented in the literature, including national records and guidelines on deadwood and forest residue rates. This analysis provides insights into which European countries have the potential or exhibit a stronger foundation for assessing the impact of advanced biofuel production on biodiversity when using forest residues as feedstock.

Relationships between deadwood and species richness or biodiversity have been found as a result of the literature review. The importance of deadwood as a component of forest ecosystems is well known today, but there are no simple and statistically based guidelines on this aspect of forest management (Lassauce, et al., 2011) (Müller & Bütler, 2010), mostly due to the highly complex relationships involved (Bütler & Schlaepfer, 2004) (Stokland, et al., 2004). This makes it difficult to elaborate a single value for a broad range of data (Ranius & Fahrig, 2006).

A higher number of curves resulted from the literature review compared to the number of thresholds. However, the number of curves were based on different metrics, different species and focusing on a specific relationship between deadwood and a second variable. Furthermore, the resulted number of 28 curves of different types with statistically positive relationship between deadwood and biodiversity are based on different species and derived from different statistical models which does not allow to easily make a robust analysis. With similar results, Laussace et al (2011), investigated the correlation between biodiversity of saproxylic organisms and different deadwood volumes descriptions, with the purpose to identify management guidelines aiming to conserve saproxylic organisms. As an example, in one occasion, a meta-analysis was rejected due to the difference in statistical methods applied that did not allow data transformation, i.e. the different types of results were not able to be part of the statistical analysis due to the nature of the data (Lassauce, et al., 2011).

Additionally, even within the same study of a single species in different regions, different threshold values for the same habitat factor can be derived, e.g., 10-70 m^3/ha for boreal forests and 10-150 m^3/ha for lowland forests and mixed-montane forest. As a result, knowledge of the response of a single species is still rather low (Müller & Bütler, 2010). Furthermore, in European managed forests, species communities are reduced (Speight, 1989) (Fowles, et al., 1999), therefore, analysis is narrowed down to those species and communities that have been recorded in occurrences and densities that can be analysed statistically (Müller & Bütler, 2010).

Thresholds are often used in scientific studies and ecological research for their ability to simplify complex relationships, understand species needs and provide decision points for ecological management in landscape conservation (Lindenmayer, et al., 2008). Defined as the "break-point" at which there is a change in a quality, researchers can establish standardised criteria that serve as references for assessing the status and predicting the response of ecological systems. These thresholds are typically based on specific ecological indicators or variables relevant to the research objectives, such as the deadwood levels evaluated in this report (Groffman, et al., 2006).

The way to assess and identify thresholds is often combined with species-habitat relationship curves. Several statistical methods for estimating values have been proposed and tested, including regression, generalised additive models, Bayesian analyses, etc. (Ficetola & Denoël, 2009). These different metrics and statistical models make it difficult to interpret and compare curves. Furthermore, the establishment of universal thresholds applicable across regions and species can be challenging due to several factors, including differences in environmental conditions and biases in data availability, such as:

1. Species-specific variation: Different species have different ecological requirements and responses to environmental conditions. Therefore, setting a single threshold may not adequately capture the ecological needs and sensitivities of all species (Müller & Bütler, 2010).
2. Regional ecological variation: Ecological processes and dynamics can vary considerably between regions and ecosystems. Factors such as climate, geology and historical land use patterns can influence species composition, habitat suitability and ecological thresholds. Therefore, a threshold established for one region may not be directly applicable or relevant to another region (Groffman, et al., 2006).
3. Data availability and research bias: Data availability and research efforts are not consistent across species or regions. Some species may have been studied more thoroughly, leading to a better understanding of their ecological requirements and the establishment of specific thresholds. On the other hand, there are data gaps or biases for certain species or regions, making it difficult to derive accurate and universally applicable thresholds (Müller & Bütler, 2010).
4. Scale and context: Thresholds may vary depending on the spatial and temporal scale of the study. Ecological processes and responses are often context dependent, influenced by factors such as landscape characteristics, management practices and historical land use legacies. Therefore, thresholds established for one scale or context may not apply at different scales or in different contexts and can even change over time for the same context (Groffman, et al., 2006) (Müller & Bütler, 2010).

Therefore, deadwood thresholds specific to species is a more appropriate metric to work with when related to certain species and geographies; even though it is still difficult to establish a rate applicable to all regions, forest types and species as some species have been studied more frequently than others. Boreal and Atlantic forests have been the most common ecosystems covered. Additional monitoring studies are necessary on a European level for different animal and insect species in temperate, boreal, and Mediterranean forest to reduce the biased existing information in the literature focusing on the Boreal forests (Bütler, 2003) (Müller & Bütler, 2010).

Due to the limited number of papers resulting from the current study, it was not possible to cover the relationship between deadwood type, tree species and animal species. More studies exploring the effects of both deadwood volume and diversity on the variation in species richness are needed (Müller & Bütler, 2010) (Seibold, et al., 2015) (Ramírez-Hernández, et al., 2019) and also referring to the habitat quality of deadwood as some of its characteristics are often more important for deadwood specific organisms than its volume (Sandström, et al., 2019) (Seibold et al., 2016; Vogel et al., 2020); characteristics that are important include deadwood position (standing or lying), size, species, and degree of decomposition (Brin, et al., 2011) (Aszalós, et al., 2020). Different organisms occupy different habitats in terms of their preferences, with many species exhibiting limited tolerance of specific microhabitat characteristics (Ruete, et al., 2017).

Based on all the above, the first selective criterion of this study for identifying and assessing biodiversity levels through deadwood as indicator within a region is the existence of a number of deadwood thresholds for different organisms in a particular country or region, and by including a higher number of species, a higher confidence is expected when using these thresholds in relationship with biodiversity conservation purposes. The thresholds selected are the result of the literature review (Table ***9***).

The existence of data on deadwood records, biodiversity guidelines in place, and the inclusion of harvesting volumes and primary harvesting residues, as part of the volumes retained for deadwood creation, should be considered as crucial information when assessing biodiversity in a forest region. Forest type and forest industries are important factors when identifying the largest drivers for harvesting residues volumes. From this perspective an ideally, intensive managed spruce forest would create higher volumes of harvesting residues. When in that country any deadwood related policies are in place, a proportion of those residues should remain in the forest for biodiversity purposes, which entails the creation of deadwood habitats for certain species and at the same time limits the sustainable availability for biofuel production. These factors have been considered for the qualitative analysis.

The quantitative analysis counts as a criterion for focus in a specific country, such as the existence of rates to which deadwood thresholds are preserving biodiversity, and the existence of harvesting residues records and/or forecasting harvesting volumes in those countries. The existence of tree retention and residue retention guidelines in the regions and countries studied were accounting as positive criteria for selecting a country to perform a biodiversity assessment, since residue volumes retention guidelines are put in place only in certain countries. Grinde et al. 2020 showed that bird community metrics had a clear and consistent positive response to tree retention, with several configurations resulting in higher total abundance, increased diversity, and higher species richness compared to stands with no tree retention (Grinde, et al., 2020). The use of retention forestry moderates negative harvesting impacts on biodiversity (Fedrowitz, et al., 2014).

Deadwood records in national inventories are available in different ways and frequency that makes the comparison of the data between the countries difficult.

At the time of writing this report, there are no EU laws specifically related to deadwood, and binding guidelines for conservation and increment of its volume are not widely in place. Even when such guidelines are in place, they are often not specific enough to be incorporated in forest management practices in each country.

National deadwood records and qualitative assessment of biodiversity guidelines

This analysis considers the existence of deadwood records in the national forest inventories, as well as biodiversity guidelines in place (which normally include references to retention volumes for deadwood creation and country's recommended deadwood thresholds as guidelines). Table 16 summarises the conclusions for each country including the findings on the above (deadwood records, and biodiversity guidelines in place), and includes deadwood thresholds from the literature, as well as the level of deadwood recorded for that particular country (Table 16).

Deadwood thresholds resulting from the literature review are species specific while national thresholds from the guidelines are generic. The thresholds provided by the national guidelines are considered as a reference for the overall required limits should the species-specific ranges from literature lie below the national range levels of deadwood threshold that would be available in the forests of that country.

Table 16: Conclusions for each country following findings on deadwood records, and biodiversity guidelines in place

Country	Deadwood recorded	Deadwood thresholds found in literature review	Species	Forest type	Biodiversity guidelines	Conclusions	
Sweden	7.6 m^3/ha	12-22 m^3/ha	Birds, beetles, fungi, red-listed species	Spruce, pine	In place	Deadwood amount in the forest has been increasing over the years, partly due to natural fatalities. Policies in place help to define best practices	✓
Finland	6 m^3/ha	20 m^3/ha	Fungi, red-listed species	Spruce, pine	In place	Biodiversity guidelines promoting residues retention in the forest are positive, provides a confident framework to operate	✓
Germany	20.6 m^3/ha	44-50 trees/ha; 5-30 m^3/ha	Woodpeckers, beetles	Spruce, silver fir, beech	In Place	Relative high amount of deadwood recorded in managed forest; regional policies in place may be more or less restrictive	✓
Austria	9.7 Vfm/ha[2]	41-60 m^3/ha	Insects, bryophytes	Spruce, silver fir, beech	In place	Biodiversity guidelines in place but no clear directive on deadwood thresholds needed in the forest	…
France	8 m^3/ha	25-70 m^3/ha	Bats, beetles	Oak, beech, birch, aspen, sorb tree, wild cherry tree	In place	Biodiversity regulations in place and deadwood recorded; however not thresholds recommended as guideline	…
Switzerland	24.2 m^3/ha[1]	1.6 m^2/ha	Woodpeckers	Spruce	In place	High amount of deadwood in the forest; thresholds provided as basal area and not an easy applicable reference	…
United Kingdom	0-10 m^3/ha	20-40 m^2/ha lying deadwood	Saproxylic organisms	Broadleaved forests	In place	Deadwood reference not provided for intensively managed forest, specific deadwood assortment limiting extrapolation of results	…
Poland	5.9 m^3/ha	15-20 m^3/ha	Birds	Pine, spruce, beech, oak, birch, alder, silver fir	In place	High deadwood volumes as an average and awareness of biodiversity conservation in the forest in place; however, there are no thresholds recommended	✗
Italy	1.7 m^3/ha	32 m^3/ha	Beetles	Ash, alder, willow, black poplar	In place	No specific guidelines on deadwood thresholds provided, low amount recorded in plantation forest; Mediterranean forest are not intensively managed	✗

[1]Includes Voralpen and Alpen regions, where the amount of deadwood is potentially higher due to limited accessibility. Without these regions, average would be 20m^3/ha in Switzerland, [2] Vfm= m^3 and is standing deadwood

✓ Criteria met … some factors under consideration ✗ no sufficient or valid criteria

Sweden, Finland and Germany have records of deadwood in their national inventories; and thresholds found as result from the literature review do contemplate more than one species. These thresholds recognise the amount of deadwood necessary in the forest for different habitats and for certain species and thus provides with a wider spectrum of biodiversity levels. Studies on extinction thresholds typically consider individual species (Fahrig, 2023) but a few past studies had considered assemblages of species (Huggett, 2005) (Radford, et al., 2005). Ultimately, the goal for conservation is not to preserve individual species, but to preserve overall biodiversity including many taxa that are poorly known (Ranius & Fahrig, 2006).

Germany presents the highest amount of deadwood recorded in a managed forest; however, the forest management guidelines are different compared to the Nordic countries, where there are higher recommended retention volumes in the forest. As an example indicated in chapter 3.3, in Sweden's spruce forest, it is allowed to take up to 70% of the harvesting residues in 50% of the harvested stands on a landscape level, meaning leaving around 30% of harvesting volumes as retention volumes in the forest (Drott, et al., 2019) and Finland's best practice promotes to leave around 1/3 of the harvesting volumes from a clearcut in the forest as retention volumes for deadwood creation, whereas Germany recommends to maintain 1 m^3/ha as retention volume (Bundeswaldinventur, 2012).

The Nordic countries and Germany present "best practice" guidelines in place as well, which allows potential calculation of retention volumes per hectare for a certain forest management unit.

Austria, France, Switzerland, and the United Kingdom have deadwood records and biodiversity guidelines including this topic but do not provide any recommendation on a management basis, and species covered by the literature thresholds are limited to one species in the case of Switzerland. Although institutional organisations in these countries do not provide with a framework of action with regards to biodiversity conservation values in the forest (deadwood thresholds), this however should not serve as a limiting factor when studying potential opportunities on those countries.

Poland and Italy do contemplate deadwood as a contributing factor for biodiversity levels in a forest and have records on their inventory for that reason. However, there is no information on the type of forest for Poland; the volumes of deadwood recorded in Italy for plantation forest are not large considering the forest area in the country. Furthermore, there are no national volumes provided in both countries' guidelines for deadwood for being appropriate to maintain biodiversity in the forest (deadwood thresholds). Environmental guidelines are not clear in Poland and Italy regarding deadwood maintenance or residue retention in the forest and thus the deadwood volume requirements are not sustainably guaranteed and so any biodiversity levels in the forest would not be easily linked to deadwood.

Finally, the driving force for the generation of harvesting residues and retention volumes from wood production in the managed forest are the surrounding industries. The Nordic countries and Germany present a high concentration of sawmills and an established industry which will ensure the sustainable production of residues as a result of roundwood harvesting, and reinforce the supply chain maturity, that will allow for a sustainable primary harvesting residue supply estimation potentially dedicated to biofuel production purposes.

Harvesting residue records and quantitative assessment of biodiversity guidelines

In addition to the qualitative analysis of biodiversity guidelines, AFRY compiled the information for each country on harvesting residues records, national recommendation of deadwood thresholds in the forest, retention volumes, forest management strategies and supply chain maturity (Table 17). Some of these data could be of use in estimating and evaluating the potential available residue from the country's forests for biofuel production. A summary table compiles the data on deadwood recorded in the forest, harvesting residues generated in the countries, retention volumes recommended by the countries following best practice guidelines, thresholds recommended on a national level and thresholds found in the literature related to specific species and forest types (Table 18).

Table 17: Conclusions for each country based on harvesting residues recorded, retention guidelines, forest management strategies and supply chain maturity (2020/2021 data)

Country	**Harvesting residues recorded**	**Deadwood thresholds recommended by the countries**	**Forest type**	**Harvesting residues official statistics**	**Forest management type**	**Retention volumes**	**Conclusions**	
Sweden	40 m^3/ha	2.5 m3/ha* to be left after harvesting	Spruce, pine	Yes	Clear cut/managed	Yes	The recording for harvesting residues refers to most intensively managed forest. Harvesting residues allows the creation of deadwood threshold in place.	✓
Finland	49 m^3/ha	20 m^3/ha	Spruce, pine	Yes	Clear cut/managed	yes	Harvesting residues recorded for clearcut areas in most intensively managed forest. Harvesting residues allows the creation of deadwood threshold in place.	✓
Germany	2.7 m^3/ha	1 m^3/ha to be left after harvesting to maintain 20 m^3/ha	Spruce, silver fir, beech	Yes	Selective harvesting	yes	Volume of harvesting residues recorded seem realistic with the deadwood volume threshold in place - note this may have regional variations. Harvesting volumes forecast in place.	✓
Austria	1.85 m^3/ha	25 m^3/ha	Spruce, silver fir, beech	No	Selective harvesting	No	Low volume of harvesting residues compared with Nordics, high deadwood target in the forest. No official harvesting volumes forecasts.	…
France	0.75 m^3/ha	No	Oak, beech, birch, aspen, sorb tree, wild cherry tree	No	Selective harvesting	No	No deadwood threshold recommended for the forest and no official recording of harvesting residues as reference for biodiversity conservation purposes.	✗
Switzerland	1.77 m^3/ha	20 m^2/ha	Spruce	Yes	Selective harvesting	No	Lower amount of harvesting residues recorded and a high deadwood target recommended. However, harvesting forecast volumes provide confidence.	…

*FSC, PEFC guidelines, estimation

✓ Criteria met … some factors under consideration ✗ no sufficient or valid criteria

Table 18: Compilation of data on deadwood records, harvesting residues and deadwood thresholds from national recommendations and results from the literature review for the selected countries.

Country	Harvesting residues generated	Deadwood recorded	Deadwood thresholds recommended by the countries	Forest type of national thresholds	Deadwood thresholds found in literature review	Species	Forest type for thresholds in literature review
Sweden	40 m^3/ha	7.6 m^3/ha	2.5 m^3/ha to be left after harvesting	Spruce, pine	12-22 m^3/ha	Birds, beetles, fungi, red-listed species	Spruce, pine
Finland	49 m^3/ha	6 m^3/ha	20 m^3/ha	Spruce, pine	20 m^3/ha	Fungi, red-listed species	Spruce, pine
Germany	2.7 m^3/ha	20.6 m^3/ha	1 m^3/ha to be left after harvesting to maintain 20 m^3/ha	Spruce, silver fir, beech	5-30 m3/ha	Woodpeckers, beetles	Spruce, silver fir, beech
Austria	1.85 m^3/ha	9.7 m^3/ha	25 m^3/ha	Spruce, silver fir, beech	41-60 m^3/ha	Insects, bryophytes	Spruce, silver fir, beech
France	0.75 m^3/ha	8 m^3/ha	No	Oak, beech, birch, aspen, sorb tree, wild cherry tree	25-70 m^3/ha	Bats, beetles	Oak, beech, birch, aspen, sorb tree, wild cherry tree
Switzerland	1.77 m^3/ha	24.2 m^3/ha*	20 m^3ha	Spruce	1.6 m^2/ha	Woodpeckers	Spruce

Sweden, Finland, and Germany provide official records of harvesting residues and best practice guidelines for residue retention in the country after harvesting operations. For the three countries, the volume of harvesting residues created surpass the deadwood threshold recommended by the country. Furthermore, in an example of an average case of harvesting volumes of 250 m^3/ha in Finland, best practices would recommend leaving 1/3 of those volumes (~80 m^3/ha) in the forest as retention volumes, or 20% of the harvesting volumes in Sweden (50m^3/ha), for species and habitat conservation purposes. From the remaining harvesting volumes not being retained in the forest, the portion of stem wood is used by the industry and the resulting primary forest residues would be potentially available for collection.

The retention volumes for Finland and Sweden would exceed the thresholds recommended for deadwood in the forest management guidelines for those countries, and hence provides with a satisfactory level of confidence for deadwood creation, despite expecting a full consumption of primary forest harvesting residues by the industry. Additionally, these three countries provide official harvesting forecast volumes, which allows direct access and estimation of potential residue removals for biofuel production over the years.

Switzerland and Austria do not meet all the above criteria; Austria presents low levels of harvesting residues compared to the recommended amount of deadwood expected in the forest and does not provide insights of harvesting residues volumes increasing/decreasing in the future, since there is no official data covering this information to date.

Switzerland recommends a high volume of deadwood as a threshold in the forest compared to the harvesting residues generated; furthermore, as it is the case for Austria, no recommended retention volumes are in place after harvesting operations. Even though deadwood creation as a consequence of natural disasters may increase the deadwood thresholds in the forest, the casualty does not allow to count for a general systematic generation of deadwood in the forest. Given the high levels of deadwood expected compared to the harvesting residues generated, it may not be appropriate to consider full removal of the residues from the forest as the absence of deadwood will affect biodiversity levels.

The ICL study shows results of primary forest residues production in Finland, Sweden, Germany and France as the highest volumes. Forest residues availability focus mostly on clearcut areas in those countries and the volumes of residues generated from those areas. Clearcut areas generate the largest harvesting volumes and have a particular focus for retention volumes for biodiversity purposes.

France does not produce official data on harvesting residues from the forest operation, lacks existing recommendations for retention volumes and has no official forecast harvesting volumes.

5 Conclusions and recommendations

5.1 Building the foundation for forest biodiversity assessments

5.1.1 Bridging the scientific data gap

Measuring biodiversity linked to deadwood involves assessing a variety of parameters such as volume of deadwood, types of deadwood, decay stages, type of forest and dependant organisms. Scientific studies to date have primarily focused on individual species e.g. on birds, beetles, and fungi, and their response to changes in deadwood volume. For example, saproxylic species diversity (richness, evenness, and composition) is often used to gauge the level of biodiversity linked to deadwood in specific forest types. The results from the literature review show challenges for the development of a valid and standard deadwood threshold based on the existing thresholds across regions and species, due to species-specific variations, regional ecological variations, limited data availability and research bias, and the small scale and context of the studies. The complexity and variability of the study designs hinder the development of a standardised methodology for measuring biodiversity and creating indexes linking biodiversity to deadwood in forests.

A larger dataset on studies performing similar methodologies in assessing the relationship between deadwood and biodiversity and studies including larger samples of species and different forest ecosystems will help to develop statistically robust curves on the relationship between deadwood and the species. In this way, it would be possible to indirectly assess the biodiversity level in an ecosystem where deadwood would act as one of the main biodiversity criteria, and how the removal of forest residues suitable to become deadwood may impact the biodiversity levels in those forests. The biodiversity assessments need to be accompanied by clearly explained standard statistical design methods including information on the deadwood, or other biodiversity-related parameters, studied species and forest types to enable direct comparison on biodiversity levels in a systematic manner between forests when possible.

Further investigation is also needed on the impact of deadwood removal on the habitat for less studied saproxylic organisms or deadwood dependant animals such as small mammals and birds. This broader understanding is crucial for establishing comprehensive deadwood thresholds for a certain forest area. In conclusion, a larger and diverse number of such studies will allow the scientific community to establish a basis for biodiversity indexes, and develop a standardised methodology for estimating biodiversity impact when formulating conservation guidelines in European forests.

To further improve the understanding on forest biodiversity and capture the complexity and richness of the ecosystem, the inclusion of other biodiversity-affecting parameters is essential to bear in mind. These parameters can be relevant to deadwood, such as deadwood size and decay stage, but also parameters quantifying genetic diversity, ecosystem diversity, indicator species, physical and environmental factors and human impact.

Last but not least, when evaluating forest health, biodiversity is not the only aspect to consider. The risks posed by forest fires are a growing concern and an important factor that must be taken into consideration for the forest management strategies and ecosystem conservation. Thin wood assortments, such as thin branches, have shown potential to increase fire risks as it may contribute as fuel during the ignition process, and there are ongoing investigations on this topic in place. The formation levels of deadwood from forest residues and the contribution of deadwood to forest biodiversity should be assessed considering the potential of forest residues to increase fire risks. This dual evaluation will help to identify the most sustainable solution for forest management and conservation strategies.

Further research support for universities and institutions in forest biodiversity provided for example by the European COST platform (European Cooperation in Science and Technology) could be used as a common basis by including systematic field deadwood observations and species related data in different forest ecosystems and under different management practices in the European countries. The systematic approach may help for habitat comparison, deadwood conservation guidelines, aiming to set wider biodiversity conservation strategies.

5.1.2 Challenges and data gaps in biodiversity across European countries

Forest residues constitute a significant resource for producing advanced biofuels. To ensure their sustainable use without detriment to biodiversity, it is crucial to have a solid scientific understanding of factors such as deadwood thresholds, as outlined and discussed in this report. Equally important for effective biodiversity assessments are the existence of detailed forest management practices and comprehensive national records that include data on parameters like deadwood density and harvesting residues generation rates across various forest ecosystems.

Concluding from this review, Finland, Sweden and Germany, covering 45% of the total harvested volume based on Eurostat data (226 million m^3 from a total of 507 million m^3 in 2021), were identified as having the best availability of both scientific research on deadwood thresholds and national data on deadwood levels, recommended retention volumes for residues and biodiversity guidelines. Despite this, significant advancements in scientific research are still necessary to include a broader array of organisms and biodiversity-affecting parameters in biodiversity assessments for more robust conclusions on biodiversity conservation limits.

Austria and Switzerland have some data, but there are current gaps in country-specific forest guidelines. For instance, guidelines on retention trees or volumes are absent, and there have been only a few research articles on quantifying deadwood thresholds for the forests in these countries. This data deficiency makes it difficult to use a rigorous biodiversity assessment. Similar forest structures in other countries with comparable ecosystems and habitats may act as a reference and be a potential solution to assess biodiversity levels related to deadwood

For the remaining countries evaluated in Central, Southern Europe, and the Baltics, no sufficient scientific data on deadwood thresholds have been identified as a result of the literature review performed. France, Italy, and Poland are countries where management guidelines referring to retention volumes or databases detailing residue records are not available, further hindering potential comprehensive evaluations of biodiversity conservation in their forests in relationship with deadwood.

5.2 Policy Implications and Future Directions in European Forest Management

Using deadwood as biodiversity criterion in forest and landscape management has become part of the biodiversity strategy of many European countries (Hodge & Peterken, 1998) (Angelstam, 2002). Existing policy frameworks inform on and drive the implementation of forest management practices and increase awareness for recording of deadwood volumes. They also provide a starting point in measuring deficits or establishing confidence levels of biodiversity based on its existing volumes in the forest.

The Kunming-Montréal Global Framework (United Nations Environment Programme, 2022) and the EU Restoration Law (European Commission, 2022) are important considerations in moving forward. In October 2024, the COP16 (United Nations Biodiversity Conference) is taking place and is focusing on supporting countries so that their National Biodiversity Strategies and Action Plans align with the Global Framework. On the other hand, the EU Restoration Law received its final approval in June 2024, which will have implications for the management of European land. These developments add to existing reporting frameworks, including the EU Supply Chain Due Diligence Act (European Commission, 2022), the EU Taxonomy (European Commission, Joint Research Centre, Battiston, S., Alessi, L., Roncoroni, A. et al., 2020), and the Corporate Sustainability Reporting Directive (European Commission, 2021) including the new European Sustainability Reporting Standard (European Commission, 2021). It is likely that some, if not all policies, will impact forest management practices one way or another. In the absence of binding measurement frameworks in many cases, this discussion is still in flux; however, given the current trajectory of the global discussion around biodiversity, a revision of current forest management practices and/or implementation of stricter biodiversity and deadwood policies could be expected. For this reason, collaboration between scientists and policy-makers is essential to develop evidence-based solutions that conserve and restore forest biodiversity while promoting sustainable forest management that balances environmental, social and economic objectives.

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