The Forest Economy and Climate Change

A REVIEW OF GREENHOUSE GAS MITIGATION IN EUROPE'S FORESTS AND FOREST PRODUCTS

July 2019

The Nature Conservancy

eit Climate-KIC

This report was prepared by The Nature Conservancy (TNC) for EIT Climate-KIC.
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ACKNOWLEDGEMENTS

This report was made possible through the support of EIT Climate-KIC, with contributions from the Reforestation Accelerator, a collaboration of the World Resources Institute and The Nature Conservancy, and additional financial support from the Children's Investment Fund Foundation, Good Energies Foundation and COmON Foundation. We also thank Diana Tuomasjukka of the European Forest Institute and Mark Wishnie, Susan Cook-Patton and Peter Ellis of TNC for reviewing drafts of this report.

Executive Summary

PURPOSE OF THE REPORT

Forests hold unique potential to mitigate climate change by sequestering and storing carbon in biomass and soils and by providing timber and other products to the economy. These forest products can reduce fossil fuel emissions by substituting for greenhouse gas-intensive alternatives. A central debate in European forest policy concerns how to manage the forest and wood product system to provide the greatest net climate change mitigation benefits.

The aim of this literature review is to characterise the state of the forestry sector in Europe and identify the key parameters that influence the greenhouse gas mitigation outcomes of managing forests to produce wood products. These findings will help to inform the development of tools and frameworks to support policy regarding the role of forest management and wood products in European climate change strategy.

KEY MESSAGES

1. Managed forest systems in Europe are diverse, ranging from even-aged plantations to uneven-aged selection harvest or coppice systems. This diversity results from centuries of management, and a large proportion of Europe's forests are still actively managed for wood production.

2. After historic deforestation and over-exploitation, European forests have been recovering in both area and carbon stocks for the past half-century. Carbon stocks in Europe's forests are increasing by more than 110 million tonnes each year. However, this sink is decreasing as Europe's forests mature and net growth begins to decline.

3. The wood product carbon pool in Europe is also increasing, but only at about 10% of the rate of the forest carbon pool. The current use of wood harvested from European forests also avoids in the region of 100 million tonnes of fossil carbon emissions through substitution compared to a zero-wood use alternative.

4. European forests also influence the climate system directly through their impacts on albedo, evapotranspiration and heat transport in the atmosphere. Research suggests that these effects are similar in importance to forests' impact on the carbon cycle, yet more work is needed to understand the subtleties of these feedbacks.

5. Maintaining or increasing forest management for wood products can in some cases result in greater overall greenhouse gas mitigation than leaving forests unharvested. Active forest management and harvest tend to outperform no harvest where (i) there is rapid forest growth and re-growth, (ii) harvested wood is utilized efficiently, (iii) a high proportion of wood enters long-lived products, (iv) product markets provide an incentive to increase forest area and (v) products have a high degree of substitution for emissions-intensive alternatives.

6. Of these five factors, substitution can be the most important in determining net greenhouse gas reductions owing to the large range of possible outcomes: substitution

factors for wood range from -0.6 to +5.1 kilograms of carbon mitigation per kilogram of carbon in the wood product. However, substitution is highly sensitive to context and assumptions about the type, footprint and amount of displaced materials, as well as the potential for re-use, recycling and cascading use of products.

7. There is robust evidence that the use of wood in construction generally provides a clear substitution benefit, given the high carbon intensity of cement, steel and other building materials. Emerging textiles, plastics and chemicals from woody feedstocks also hold great promise in reducing fossil emissions. Evidence for the substitution benefits of other short-lived products such as paper and packaging is much more equivocal; in some cases (e.g. graphic paper) there are no obvious alternatives for which wood products can be said to substitute.

8. Critical to all assessments is the counterfactual or reference scenario: What would have happened in the absence of a management or policy choice? This is especially important to the estimated benefits of forest product substitution. The appropriate counterfactual is not purely a scientific question, but depends on the specific economic, ecological and cultural context, and could vary widely for different forests across Europe.

9. Wood production and climate change mitigation are rarely the only values that forests provide; true sustainability must also account for the crucial protective, recreational and cultural roles of forests in Europe.

RESEARCH AND POLICY NEEDS

There is a clear need for frameworks that consider holistically the climate impact of wood products and forest supply chains. Such frameworks could integrate information on forest carbon sequestration, efficiency of wood utilization, duration of carbon storage, scale of potential markets and environmental values with existing metrics such as substitution factors to provide a fuller picture of the sustainability of a given wood product.

For some product types and end uses (e.g. wood in construction), there is already considerable research quantifying lifecycle emissions across various case studies. Deeper insights could come from making explicit the conditions and assumptions underlying the different conclusions across these studies. At a larger scale, such product-level assessments need to be complemented by region-wide system modelling to articulate coherent future visions for the European forest sector. Finally, more research is needed to understand the life cycle emissions of emerging wood products such as biochemicals and textiles, as well as emerging non-wood alternatives such as low-carbon cement.

This review also makes apparent several low-regrets policy principles that could support the contribution of the forest sector to climate change mitigation. Where forests are managed, efficient use of harvested wood and residues, as well as recycling and cascading use of products, should be encouraged. There is also robust evidence that the use of sustainably-sourced wood in long-lived application such as construction reduces net greenhouse gas emissions. On the forest management side, sustainably increasing productivity in currently managed forests can increase carbon sequestration. Finally, policy must also recognise the multiple values associated with forests, and ensure that forests with high biodiversity, cultural significance or protective functions are protected in strategies to reduce emissions from the forest sector.

UNITS AND ABBREVIATIONS

Units

kg – kilograms
t – tonnes
Mt – million tonnes
Gt – billion tonnes

ha – hectares
Mha – million hectares

m^3 – cubic metres
Mm^3 – million cubic metres

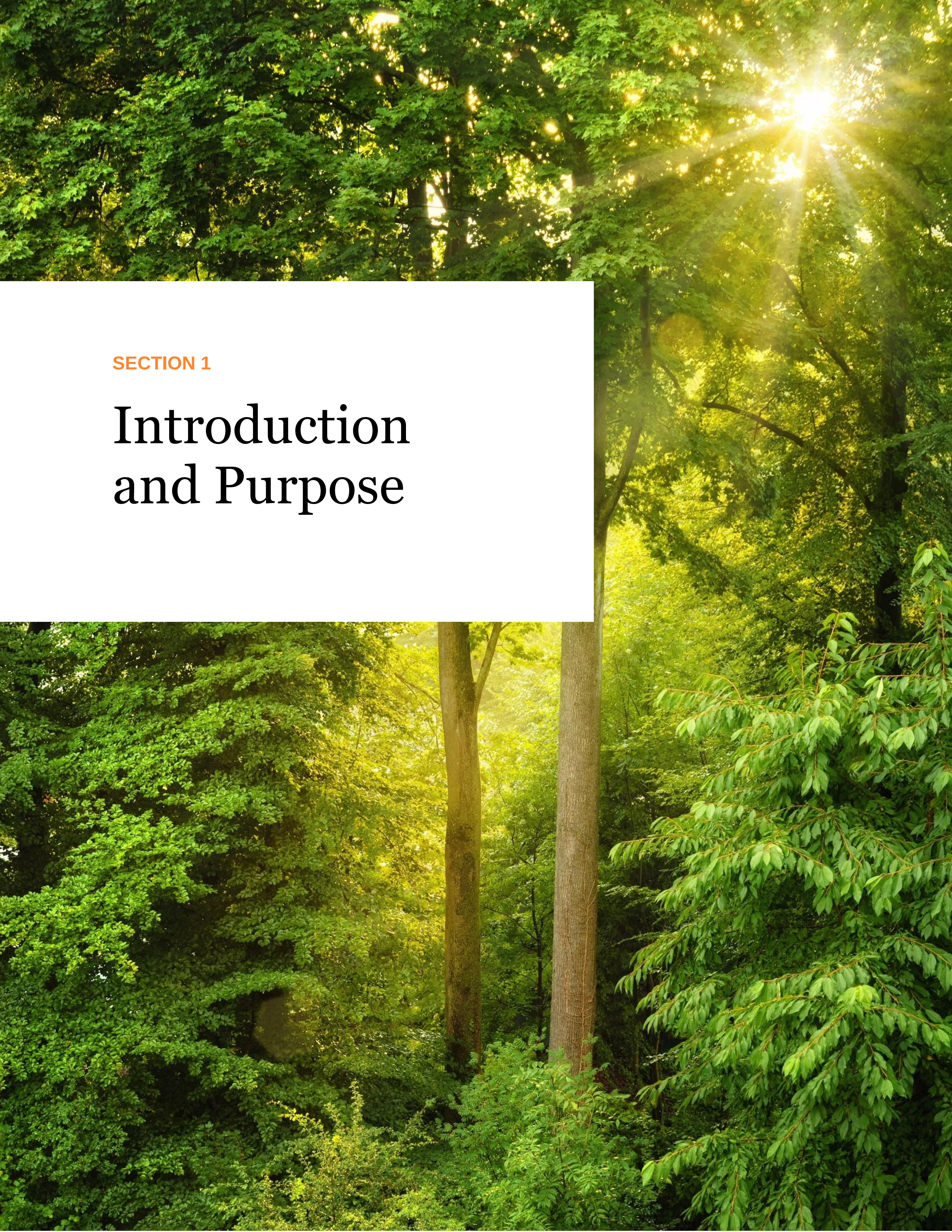
Abbreviations

C – carbon
CLT – Cross-Laminated Timber
EU – European Union
GHG – Greenhouse Gas
LCA – Life Cycle Assessment
MAI – Mean Annual Increment

Note on carbon accounting units

This review reports carbon sequestration, storage and emissions in units of kilograms or tonnes of carbon (kg C or t C), rather than in kilograms or tonnes of carbon dioxide (kg CO_2 or t CO_2). This is to provide a common unit of comparison for carbon stocks and flows that remains consistent and meaningful whether the carbon under consideration is in the form of CO_2 gas, or is stored in solid form in biomass, soils or wood products.

One kilogram or tonne of carbon is equivalent to 3.67 kilograms or tonnes of carbon dioxide, respectively.



SECTION 1

Introduction and Purpose

European Forests and Climate Change

Research led by The Nature Conservancy has highlighted the enormous importance of Natural Climate Solutions in sequestering carbon, mitigating greenhouse gas emissions and meeting internationally agreed climate goals (Griscom et al., 2017). Of all Natural Climate Solutions, conservation, restoration and better management of the planet's forests represent two thirds of the total mitigation opportunity in the land sector in 2030.

Forests fulfil many functions and influence the climate through several pathways. First, growing forests remove carbon dioxide from the atmosphere and store carbon in the form of biomass. In the European Union, photosynthesis and tree growth in forests represents a net sink of CO_2 from the atmosphere of about 10% of gross greenhouse gas emissions (Forest Europe, 2015).

Second, forests are also harvested to produce wood and other products for use as a material, fuel and feedstock across a large and growing range of sectors. Harvest and processing lead to the release of some of the carbon stored in forest biomass, but the materials can, in some cases, remain in use for years to centuries, locking up the carbon they contain in products or landfill and preventing re-emission to the atmosphere (Nabuurs et al., 2017).

Third, use of such wood-based products and fuels can reduce fossil fuel and industrial emissions from the economy through substitution, provided the wood product is displacing an alternative with a higher carbon footprint (Leskinen et al., 2018).

Finally, and at a larger scale, forests also exert a local and global biophysical influence on the climate system through a number of pathways (Alkama & Cescatti, 2016; Luyssaert et al., 2018), in addition to their impacts on greenhouse gases.

Presently, there is an active policy debate in Europe about how to manage the continent's forests in order to maximise their contribution to climate change mitigation over the 21st century. Where should policymakers promote greater management of forests for products, and where should they seek to constrain harvest and restore carbon stocks on the landscape? Under what conditions should governments encourage greater use of wood in materials and energy generation to help reduce fossil fuel emissions, and where are these benefits illusory

While there has been much research seeking to answer these questions, differences in scope and assumptions have led to dramatically different conclusions, generating confusion and conflicting policy prescriptions.

Climate-oriented forest policy requires a holistic perspective, encompassing the multiple ways that forests and wood products contribute to climate change mitigation, as well as the multiple timescales on which these processes operate. It also requires an understanding of the limitations of scientific and modelling studies in providing universal recommendations; existing studies have shown that the climate outcome of a given policy scenario depends on complex factors including local context, market dynamics, technological changes and management decisions.

Purpose of the Report

The purpose of this first report is to summarise the state of knowledge regarding the role of forests and wood products in climate change mitigation in Europe, to identify the key conditions and assumptions that influence mitigation outcomes in a given forestry system, and to propose a set of research and policy priorities for the European Forest Economy.

Ultimately, the report seeks to inform the development of new frameworks to support decision-making concerning the climate benefits of wood product use in Europe. The long-term aim of such a framework is to characterize the conditions under which the use of certain materials in the EU can deliver the greatest long-term benefits to climate change mitigation, and to clearly identify the key factors determining the climate outcome from a forest management perspective. Such a framework would be highly instructive to policy makers.

This review document synthesises recent literature to answer the following questions:

- What is the state of Europe's forests, and how are they currently managed?
- What are the most important forest products in Europe, and in which countries are they primarily sourced?
- What are the ways in which EU forests contribute to climate change mitigation?
- What are the most important factors determining whether there is a net climate benefit from harvesting forests for products?
- What is the state of existing knowledge and analysis on the substitution impacts of key wood-based materials, and what factors drive the variability in results?

The focus of this review will be on forest carbon sequestration, forest management and the life cycle climate impacts of solid wood products. This review will not examine use of woody biomass for energy in depth, since it is itself a highly complex topic and the subject of extensive scientific and policy debate (Repo et al., 2015; Söderberg & Eckerberg, 2013). However, bioenergy is an increasingly important driver of European forest management, and is a key component of many EU countries' forestry policies (Forest Europe, 2015).

Section 2 first reviews the state of the forestry sector in Europe, including the different forest management systems commonly practised. Sections 3 and 4 examine in more depth the ways that forests influence the climate in Europe, how these factors are affected by management and the potential for substitution to reduce emissions across the economy. Finally, Section 5 summarises the key conclusions, knowledge gaps and uncertainties in the current literature, and identifies the most important considerations that will need to be effectively addressed in developing a holistic framework for assessing the greenhouse gas benefits of wood products.

SECTION 2

The European Forest Sector

The State of Europe's Forests

Europe has the second highest proportion of forest cover of all continents after South America, with 215 million hectares (Mha) of forests covering 33% of its total land area (Forest Europe, 2015). Countries with the highest percentage of remaining forest cover today include Finland (73%), Sweden (68%), Latvia (54%), Estonia (49%) and Austria (47%). Iceland (0.5%), Ireland (11%), the Netherlands (11%) and the UK (13%) are the least forested (Forest Europe, 2015).

Despite being intensively managed, Europe's forests are also growing both in extent and density. Forest area increased by 0.7 million hectares (Mha) per year in the 25-year period to 2015, with the fastest rate of expansion in Southern and Western Europe. Total growing stock is also increasing by 403 million cubic metres (1.2%) per year (Forest Europe, 2015), following a long-term trend of forest replanting and recovery from intensive deforestation and forest utilisation before 1950 (Nabuurs et al., 2013).

46% of Europe's forests are predominantly coniferous, and such forests are prevalent in the Nordic and Baltic states (representing 65% of forest area). A further 36% are broadleaved, with the remainder being mixed forests. Two thirds of Europe's forests are even-aged, representing either forests actively managed for timber production or areas that have been replanted or reforested in the past two centuries (Forest Europe, 2015; Nabuurs et al., 2013).

European Forest Management

European forests are among the most actively managed in the world, with the lowest proportion of undisturbed forests of any region (FAO, 2018). European forest management also has a long history, resulting in a huge diversity of traditional forestry systems.

The majority (87%) of Europe's forests are classed as "semi-natural", constituting mostly native and naturally-regenerated forests that are actively managed or have been disturbed in the past, as well as some former plantations that are no longer actively managed (Forest Europe, 2015). A large proportion of these forests are currently managed actively for wood production, although this can vary from commercial management for sawtimber through to informal firewood harvest. Some forests are managed towards one primary product (e.g. pulp and paper in Spanish eucalypt plantations), while others may produce multiple products from a single forest (e.g. sawn wood, pulpwood and residue bioenergy in Swedish spruce forests) (Duncker et al., 2012). More than 30 million hectares of forests in Europe are protected from harvest, with the purpose of protecting biodiversity, soil, water or landscape (Forest Europe, 2015).

Listed below are short descriptions of some representative forest management systems prevalent in Europe, spanning different forest types, products and degrees of management. However, in Europe such systems occupy positions on a spectrum of management intensities, rather than representing truly discrete categories:

TIMBER PLANTATION SYSTEMS

Plantation forests, often referring to intensively managed forests planted on previously unforested land, cover only 9% of Europe's total forest area, but make up more than half of all forests in the UK, Ireland, Belgium, Denmark, Iceland and Malta (Forest Europe, 2015).

Plantation forests are predominantly coniferous trees such as pine and spruce species in Northern and Western Europe, with South-West Europe (Spain and Portugal) also containing significant areas of eucalyptus. Around half of this area represents exotic species (Forest Europe, 2015)

Trees are typically fast-growing species, often of genetically-improved material, and often comprise a single species, although sometimes contain a minority of other species to improve diversity (Duncker et al., 2012). Fertilisation and other inputs may be used to increase growth and reduce weeds or disease risk.

In the North, softwood plantations are typically thinned a number of times during a 35- to 50-year rotation to produce pulpwood, then clear-felled to produce high-value sawtimber before replanting of the next generation of crops. Eucalypt plantations in the South-West, in contrast, tend to be managed on short rotations (10-12 years) to produce pulpwood (Duncker et al., 2012).

EVEN-AGED MANAGEMENT OF SEMI-NATURAL FOREST

The dominant form of production-oriented forest management in Europe is medium-intensity, even aged management of semi-natural forest stands to produce wood. It is dominant in the major timber producing regions of Northern Europe, and is also widely practiced in managed coniferous forests throughout Central and Eastern Europe, and to a lesser degree in broadleaved forests such as beech and oak (Brunet et al., 2010).

It differs from plantation systems in generally using naturally-occurring species, in taking place on historically forested land, and in typically employing longer rotations and reduced intensity of management, but there is a blurred boundary between the systems. In particular, many coniferous forests currently managed in this way across temperate Europe were converted from broadleaf or mixed forestry systems, or replanted with conifers after earlier deforestation of broadleaf forests (Brunet et al., 2010; Naudts et al., 2016).

In these systems, native, economically valuable species such as pine, spruce or beech often dominate the forest stand, alongside a minority of other species (Brunet et al., 2010). In some cases, trees are actively replanted after harvest, especially in northern Europe, but naturally-regenerated stands are also widespread (Duncker et al., 2012; Forest Europe, 2015).

Rotation times are longer than in plantation systems, especially in slower-growing boreal forests, and can extend to 80-120 years or more (Brunet et al., 2010; Mcgrath et al., 2015). Stands are usually harvested by clear-felling, followed by replanting, or through systems such as shelterwood cutting or leaving seed trees that aid natural regeneration of the next rotation (Brunet et al., 2010; Duncker et al., 2012).

UNEVEN-AGED MANAGEMENT OF SEMI-NATURAL FORESTS

Many semi-natural forests in Europe, especially in the Baltic states and the South-East, are still managed under low-intensity, uneven-aged management systems (Diaci et al., 2011). Under such systems, harvest tends to be of single trees or groups of trees that have reached a specified diameter or maturity, rather than felling of an entire stand (Duncker et al., 2012). These forests thus typically contain a mixture of species and ages in more diverse and structurally-complex forest stands. With biodiversity, recreational value, aesthetics and resilience becoming ever more important goals in forestry, such uneven-aged management of forests is gaining popularity even among commercial forest managers (Diaci et al., 2011; Thurnher et al., 2011).

While uneven-aged management is becoming more widespread in coniferous forests, it is more commonly associated with mixed and broadleaved forests. This is in part to the high value attained by large-diameter hardwood logs, as well as the shade tolerance of common broadleaved species such as beech, which increase the viability of selection harvest (Brunet et al., 2010; Diaci et al., 2011).

Uneven-aged systems tend to be less intensive than their even-aged counterparts. In general, forest management interventions are restricted to thinning, pruning and harvesting, with perhaps planting of target species where natural regeneration is not sufficient (Duncker et al., 2012).

COPPICE FORESTS

Historically, as much as 20-25% of Europe's forest area was managed as coppice (Mcgrath et al., 2015), a form of short-rotation management of broadleaved trees in which multiple stems are allowed to regenerate from a cut stump, producing large volumes of small-diameter, irregularly shaped timber (Unrau et al., 2018). In an active coppice, growing stems are cut at intervals usually of 15 to 30 years, creating a unique type of even-aged woodland.

As demand for fuelwood has been replaced by fossil fuels, and demand for high-quality sawtimber has increased, many coppices have been abandoned or else replaced by "high forest" (Unrau et al., 2018). Remaining coppices cover between 8 and 20 million hectares across Europe, mostly in Eastern and Southeastern Europe (Forest Europe, 2015; Unrau et al., 2018). As one of the oldest forms of forest management in Europe, coppices represent mature ecosystems in their own right, and abandoned coppices can suffer decreases in biodiversity and productivity (Unrau et al., 2018).

Rising demand for low-carbon energy is renewing interest in fast-growing coppice systems, especially using fast-growing species on short rotations of only 5-10 years (Unrau et al., 2018).

OTHER EUROPEAN FORESTRY SYSTEMS

In addition to the four archetypes described above, there is a huge diversity of other variations of forestry and agroforestry systems practised across Europe. Notable examples include harvest of natural cork forests in South-West Europe, cultivation of fruit and nut trees across the continent and informal firewood harvest. Such systems are smaller in volume than commercial timber production but may present important opportunities for biodiversity benefits and climate change mitigation.

Wood Production and Use in Europe

Annual roundwood harvest in the European Union totalled 451 million m^3 (Mm^3) in 2015. 78% of this total was "industrial roundwood", which includes sawn wood to be used in construction and wood of various sizes and qualities used to create a wide range of processed wood products (Forest Europe, 2015). The remaining 22% comprises fuelwood, including both logs for small-scale and community use and wood to be converted to chips, pellets, charcoal or other fuels for use in power generation or industrial processes (Forest Europe, 2015). Since much fuelwood harvest is informal, it is likely to be underreported (EIT Climate-KIC, 2018), but even so makes up more than half of reported wood harvest in France, Denmark, the Netherlands, Italy and Cyprus (Forest Europe, 2015).

FIGURE 1: REPORTED ROUNDWOOD PRODUCTION FOR THE TWELVE LARGEST WOOD PRODUCERS IN THE EUROPEAN UNION IN 2015. SOURCE: EUROPEAN COMMISSION (2018A)

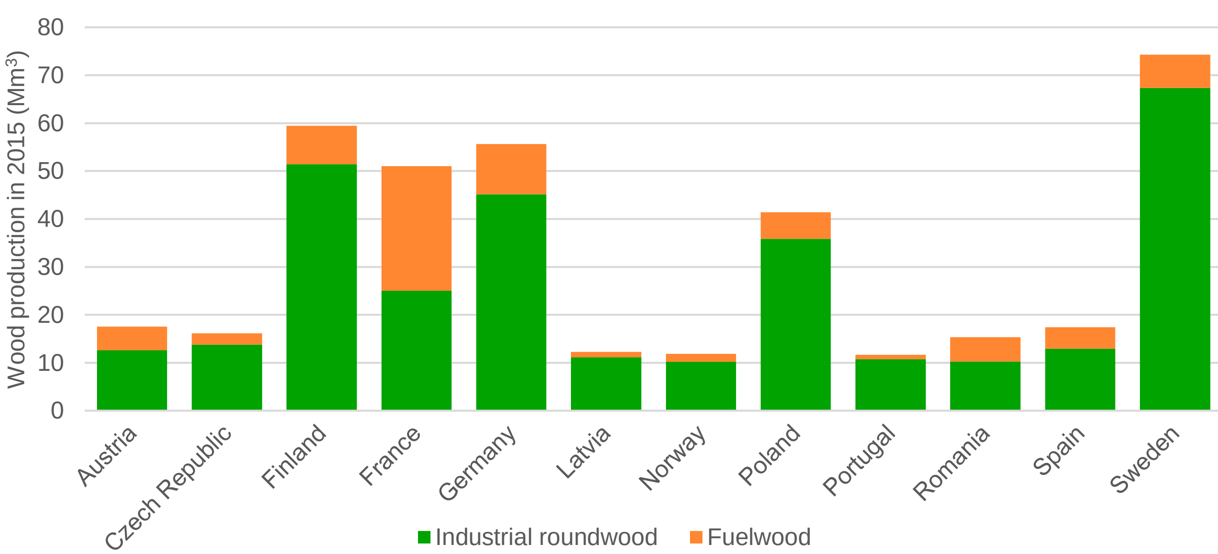


Figure 1 shows the reported fuelwood and industrial roundwood harvest in the top twelve wood producers in Europe in 2015.The largest producers of industrial roundwood, the source material for most durable wood products, are Sweden (67 Mm^3/year), Finland (51 Mm^3/year), Germany (45 Mm^3/year), Poland (36 Mm^3/year) and France (25 Mm^3/year), together making up about two thirds of all European production (European Commission, 2018a). Table 1 summarises production of different product categories across the European Union.

Very little data are available on emerging wood products such as glued-laminated timber or cross-laminated timber in construction, or emerging biomaterials such as rayon (European Commission, 2018a). Glulam and CLT production appears to be focused in central and Eastern Europe, with Austria, Slovakia and Lithuania among the few countries reporting significant production.

TABLE 1: BREAKDOWN OF EU PRODUCTION OF PRIMARY WOOD PRODUCTS IN 2015

Product	Total EU Production (2015)	Biggest producers
Industrial Roundwood	349.6 million m^3	Sweden, Finland, Germany, Poland
Sawn wood (for use in construction, furniture etc.)	*104.1 million m^3*	*Germany, Sweden, Finland, Austria*
Wood-based panels (e.g. plywood, fibreboard, oriented strandboard)	*64.4 million m^3*	*Germany, Poland, France, Spain*
Wood pulp (for paper, packaging, sanitary products)	*36.2 million tonnes*	*Sweden, Finland*
Wood Fuel	>101.0 million m^3	France, Germany

Trends in Growth and Harvest in Europe's Forests

An oft-quoted statistic is that net annual growth in timber volume in European forests exceeds wood removals and has done consistently for several decades in spite of increasing harvest (Forest Europe, 2015; Nabuurs et al., 2013). European forestry is therefore considered sustainable in terms of timber volume and carbon stocks, leading some commentators to argue that Europe has ample opportunity to more fully utilise its wood resources by expanding harvest.

However, the balance of increment to removals varies across Europe, and does not in itself indicate a growing and sustainable forest base. In Sweden, Austria and the Czech Republic, for example, removals nearly equal or even slightly exceed increment, indicating lower potential to increase harvest in these countries. Several forested countries in Eastern Europe, including Bosnia and Herzegovina, Estonia and Sweden, lost between 0.5% and 4% of their forest area between 2005 and 2015 despite overall increases in timber volume (Forest Europe, 2015).

Additionally, unharvested annual increment does not imply that forests should be more intensively harvested. Much of the current growth is the result of reforestation or recovery from overexploitation in the past (Nabuurs et al., 2013), and does not necessarily indicate under-utilised productive capacity. Similarly, at least 14% of Europe's forests are protected to preserve biodiversity, with more than half designated for other protective purposes (Forest Europe, 2015). To ensure a healthy and sustainable forest sector, productive functions must be reconciled with the need to sustain other protective, ecological and cultural values of forests.

SECTION 3

Climate Change Mitigation in European Forests

Carbon Stocks and Sinks in Europe's Forests

The European forestry sector has been a net carbon sink since at least the 1950s (Luyssaert et al., 2010; Nabuurs et al., 2013). This reflects natural recovery after centuries of deforestation and over-exploitation of forest resources, as well as deliberate reforestation efforts and improvements in forest management in the past fifty years (Nabuurs et al., 2013).

Forests of the European Union contain carbon stocks of 9-10 billion tonnes of carbon (Gt C) in living biomass (Forest Europe, 2015; Pilli et al., 2017) and an additional 2.7 Gt C in dead wood and litter at any one time (Pilli et al., 2017). Carbon stocks in the wider European region may be 30% higher, although fewer data are available (Forest Europe, 2015). This section will thus focus specifically on the EU.

"Forests of the European Union contain carbon stocks of 9-10 billion tonnes of carbon (Gt C) in living biomass."

FIGURE 2: ESTIMATED ANNUAL FLOWS OF CARBON IN EUROPEAN FORESTS IN 2000-2012, FROM MODELLING OF 26 EU COUNTRIES BY PILLI ET AL. (2017). COLOURED BOXES REPRESENT NET ANNUAL CHANGE IN CARBON STOCKS. ARROWS WITH GREY BOXES REPRESENT FLOWS OF CARBON BETWEEN STOCKS. LOSS OF DEADWOOD AND LITTER CARBON REFLECTS DECOMPOSITION AFTER HISTORIC DISTURBANCES. "EXISTING FOREST" REFERS TO ALL LAND THAT WAS FORESTED IN THE YEAR 2000. "A&R" REFERS TO AFFORESTATION AND REFORESTATION, AND REPRESENTS THE UNFORESTED LAND THAT RETURNED TO FOREST BETWEEN 2000 AND 2012.

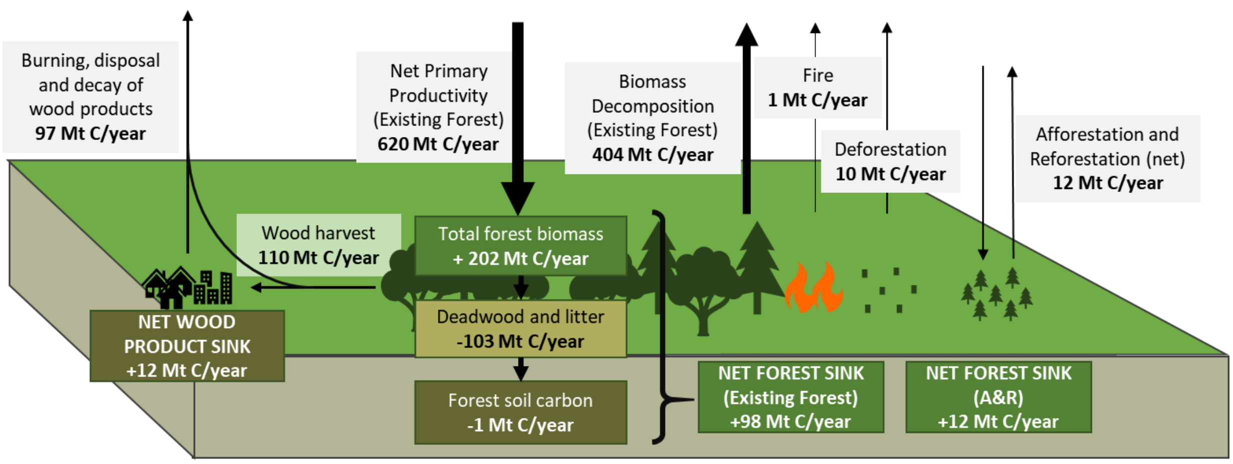


Figure 2 shows the estimated carbon flows through the forests of 26 EU countries between 2000 and 2012, based on a combination of inventory data and forest ecosystem models (Pilli et al., 2017). Of the total carbon captured by plant growth in forests each year (the net primary productivity), approximately two thirds is returned to the atmosphere by herbivory or decomposition. A further one sixth (110 Mt C per year) is harvested by humans for fuel or products, and about 2% (11 Mt C per year) is lost through natural disturbances or deforestation, leaving a net sink within standing forests of about 98 Mt C per year. Additionally, afforestation and reforestation of eight million hectares between 2000 and 2012 led to additional net sequestration over that period of 12 Mt C per year. Uncertainty in these figures is considerable, but, accounting for forest growth, decomposition, fire, natural disturbances, wood harvest and soil losses, EU forests were a net sink of about 110 Mt C per year (400 million tonnes of CO_2 per year) over that period.

An additional 110 Mt C were harvested each year from forests to produce wood products, of which fuelwood made up about one quarter. Most of this carbon in newly harvested wood products is either rapidly re-emitted (in the case of fuelwood or pulp wood) or balanced by emissions from existing wood products at end-of-life (e.g. for construction materials). However, more carbon appears to be stored as products today than is being lost from the wood product pool, resulting in a net increase in wood product storage (including exported wood) of approximately 12 Mt C/year (Pilli et al., 2017).

The use of wood products and energy in place of other materials and fuels also avoids greenhouse gas emissions from fossil fuel and cement use. Attempts to quantify the total benefit are inherently speculative, since they must compare present emissions to a hypothetical scenario without significant use of wood as a material or fuel. However, studies of substitution factors (See section 4) suggest that, depending on the sector, the avoided emissions from wood use as material or fuel are comparable to the carbon contained in the wood consumed (Leskinen et al., 2018; Sathre & O'Connor, 2010; Smyth, Carolyn et al., 2017), suggesting a total additional greenhouse gas mitigation of a similar magnitude to net sequestration in Europe's forests .

Overall, the European forest sector is currently a net sink of about 120 Mt C/year, 90% of which represents increasing carbon stocks within forests. This is equal to about 10% of gross greenhouse gas emissions from fossil fuel use and industry in the EU (European Commission, 2018b). However, evidence suggests the strength of this sink is declining over time. The most significant factor is simply that Europe's forests are aging. Older forests grow more slowly on a per-hectare basis, and emit more carbon from decomposition, reducing the net sink per hectare in existing forests. Increases in gross deforestation due to land use pressures, as well as rising rates of natural disturbances, are more minor pressures that also reduce carbon accumulation (Nabuurs et al., 2013). The use of renewable wood-based materials and fuels also avoids the use of greenhouse gas-intensive alternatives, providing an additional emission reduction benefit comparable in scale to the forest sink.

Key findings:

Overall, European forests are a net sink of about 110 Mt C/year, mostly due to net growth in existing forests.

An additional 110 Mt C are harvested each year from EU forests. About three quarters of this is used for products and about one quarter as fuelwood.

The EU generates a net increase in wood product storage (including exported wood) of 2-12 Mt C/year.

More carbon appears to be being locked-up in new products today than is being lost (end of life) from the wood product pool.

Europe's forests are, however, aging and slowing down their growth and sequestration.

Related research indicates that there is potential to significantly increase the magnitude of greenhouse gas mitigation provided by EU forests. A 2017 analysis suggested that "climate-smart forestry" applied across the sector could provide an additional 120 Mt C/year in net greenhouse gas mitigation through a combination of enhancing growth in existing forests (26 Mt

C/year), reducing deforestation and disturbances (10 MtC/year), afforestation and reforestation (17 Mt C/year), establishing forest reserves (17 Mt C/year) and substitution for materials and energy (12 Mt C/year and 38 Mt C/year, respectively) (Nabuurs et al., 2017). While these are likely upper limits, it is clear that there are material opportunities to increase the contribution of Europe's forests to climate change mitigation.

Biophysical Effects of Forests on the Climate

Stretching across more than a third of Europe's land area, forests also have profound effects on local and regional climate through their impacts on albedo, transpiration, heat transport, air circulation and emission of climate-active organic compounds (Anderson et al., 2011; Luyssaert et al., 2018; Unger, 2014). Changes in forest cover (deforestation or afforestation/reforestation), in particular, can have significant biophysical effects on the climate system, but forest management, especially shifts between coniferous and broadleaved species, can also be significant (Luyssaert et al., 2018).

The most important biophysical factors appear to be changes in albedo and in transpiration. Forests, especially darker, evergreen coniferous forests, tend to absorb more incoming solar radiation than grasslands, especially in the boreal zone of Northern Europe where the land surface is covered in white, highly-reflective snow for a large part of the year (Anderson et al., 2011). Expansion of forest cover, and especially of coniferous species favoured by commercial forestry, can darken the land surface and cause more solar energy to be absorbed. In boreal regions, the resulting climate warming effect can be strong enough to outweigh any benefit to the climate of increased carbon storage.

Conversely, trees have been shown to provide a local surface cooling effect through driving transpiration, which absorbs heat from the environment in the process of evaporating water (Anderson et al., 2011). Again, broadleaved forests tend to have a stronger cooling effect than coniferous forests. The large-scale shift from broadleaved to coniferous forests in the past two centuries has therefore likely contributed to regional warming in Europe (Naudts et al., 2016). Increased evapotranspiration in forests can also affect cloud formation and rainfall patterns, driving further climate shifts (Luyssaert et al., 2018).

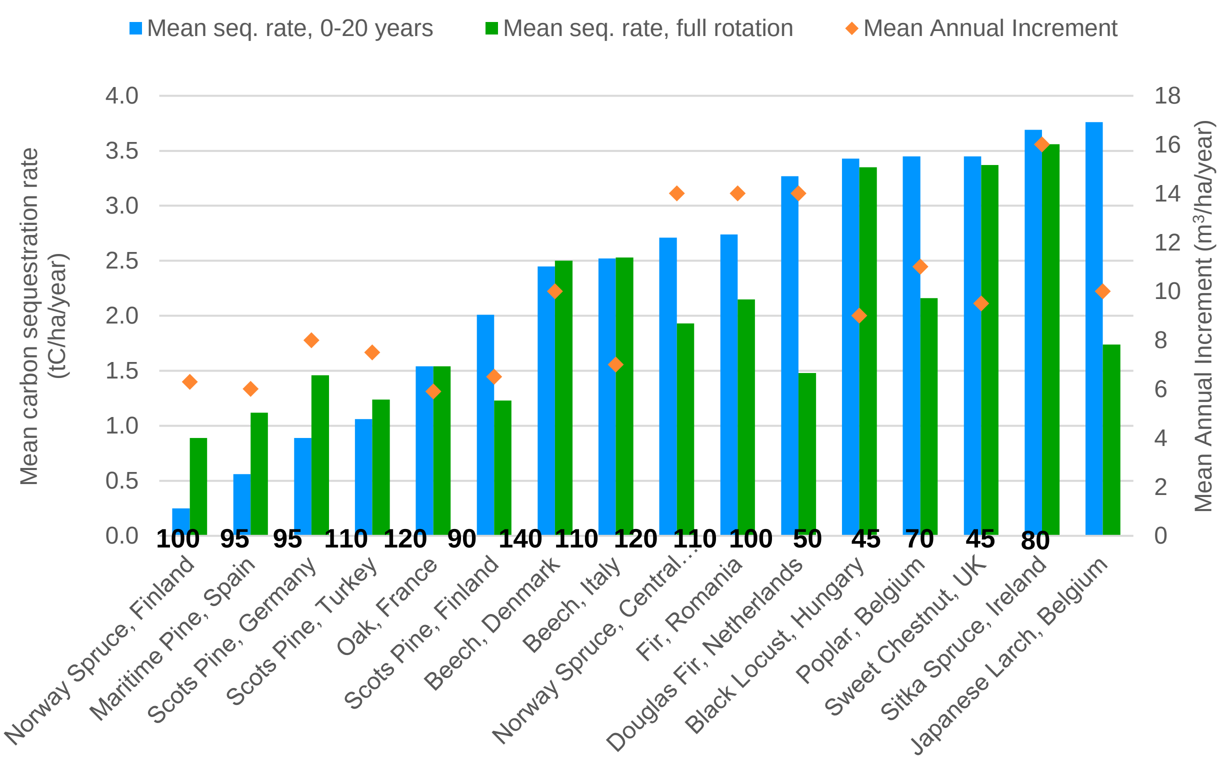
In designing holistic strategies to mitigate climate change through European forestry, it will be important to be mindful of the biophysical role of forests, as well as their roles in CO_2 sequestration and wood production. A study by Luyssaert et al. (2018) modelled forest management scenarios designed to maximise CO_2 absorption and wood product substitution, and found that such a focus could drive countervailing changes in surface albedo and cloud cover that fully neutralized the benefit from reduced GHG emissions, largely through a presumed shift towards productive coniferous species. While research into these effects continues, European forest policies should be aware of the potential for adverse climate outcomes from expansion of boreal forests. Conversely, there is evidence that broadleaved forests, while sometimes lower-yielding than coniferous species, can more effectively contribute to local and regional climate cooling.

Growth and Sequestration Rates in Europe's Forests

Europe's forests vary widely in their growth rate and rate of carbon sequestration into biomass and soils, reflecting differences in species, age, climate, ecology, soil conditions and management. Typically, the highest growth and carbon sequestration rates are associated with productive coniferous or exotic species, with high rainfall, temperate climate and intensive management (Duncker et al., 2012; Nabuurs & Schelhaas, 2002).

Growing forests, managed or natural, tend to follow a sigmoidal growth and sequestration curve: Carbon sequestration in a newly-established or regenerating forest is low for the first years (up to a decade or more), then growth rapidly increases and sequestration peaks from an age of about ten to forty years, depending on the forest (Nabuurs & Schelhaas, 2002). As forests accumulate biomass, the balance between sequestration and decomposition shifts and net sequestration declines to maturity. In managed forests, thinnings and harvest also cause emissions and affect the growth profile of the remaining stand (Nabuurs & Schelhaas, 2002).

FIGURE 3: ILLUSTRATIVE MEAN ANNUAL INCREMENT (MAI) AND SEQUESTRATION RATES FOR TYPICAL EUROPEAN MANAGED FORESTRY SYSTEMS, TAKEN FROM NABUURS & SCHELHAAS (2002). C SEQUESTRATION RATES INCLUDE BIOMASS, SOIL AND CARBON STORAGE IN PRODUCTS FROM THINNINGS. FIGURES AT THE BASE OF COLUMNS INDICATE TYPICAL ROTATION PERIODS IN YEARS.



Average sequestration rates in regenerating natural forests range from below 1 tonne per hectare per year (t/ha/year) in slower-growing and mature forests in dry climates to about 3 t/ha/year in more favourable conditions (Aosaar et al., 2016; Carrara et al., 2003; Hytönen & Saarsalmi, 2015; Salazar et al., 2010; Uri et al., 2012). Average sequestration rates in typical

European forests used for timber production, over a full rotation, range from around 0.9 tC/ha/year in slow-growing boreal forest to more than 3.5 tC/ha/year in more intensive systems in rainy, temperate climates (Fig. 3). While coniferous species tend to produce higher yields of merchantable timber, broadleaved stands can achieve equal or higher carbon sequestration rates when the whole ecosystem (all living and dead biomass, soil and products) is considered (Nabuurs & Schelhaas, 2002), while also contributing to lower albedo.

Whilst clear cut systems of management, as are typical in plantations and other planted, even-aged systems, sequester carbon during growth, they typically then reduce biomass carbon on the harvested stand to the lowest levels, especially if residues (slash) and roots or stumps are also removed (Keith et al., 2015). Continuous cover forestry, and to a lesser degree even-aged forestry systems based on natural regeneration, such as seed tree, shelterwood or coppice systems, maintain a higher level of carbon on the landscape and can aid regeneration after felling (Zielke et al., 1999). In any case, most even-aged forestry systems tend to consist of a patchwork of stands of different ages within a forest landscape, maintaining a steady average carbon stock (Vance, 2018).

To Harvest or Not to Harvest: Drivers of Climate Outcomes in Managed Forests

One of the central questions of European forest and climate policy is this: to what degree should policymakers encourage greater harvest of forests and use of forest products to drive reforestation, increased growth rates and product substitution, and to what degree should they aim for reduced harvest, close-to-nature forestry and conservation of current forest carbon stocks?

Many studies have been published on either side of this debate, using modelling and/or empirical data to quantify the net greenhouse gas emissions associated with one strategy over another from the scale of a single forest stand to the whole forest sector. Yet the chief result of these studies is that the question does not have a single answer. The greenhouse gas outcome depends on a multitude of factors concerning both the system under study and the scope and assumptions of the analysis.

A brief review of the literature shows that there are a few main drivers and assumptions that most impact the greenhouse gas mitigation outcome in each case:

1. Decisions about the scope and scale of the analysis, such as whether and how to account for substitution effects, or whether the analysis focuses on a single forest stand or a larger, more heterogeneous forest landscape.

2. The forest system under consideration, including such factors as the climate and growth rate, whether reforestation or deforestation is assumed to occur, the efficiency of harvest and the fate of harvested wood.

3. Assumptions about the context and wider system in which the analysis is situated, including, most crucially, the choice of baseline or counterfactual against which the modelled scenarios are compared.

Across each of these three categories, assumptions around substitution, and the degree to which it occurs in a given system, are among the most universally important factors driving the conclusions.

FACTOR 1: THE SCOPE AND SCALE OF THE ANALYSIS

The conclusions of a study depend first and foremost on how it frames the research question and the unit of analysis. Studies that include more components of the system, and model different stocks and flows of carbon in more depth, often provide very different conclusions to those that consider a smaller or simplified unit of analysis.

In forest management modelling, this most notably occurs with the choice of whether and how to model substitution effects (Keith et al., 2015; Vance, 2018). Studies that do quantify substitution (Eriksson et al., 2011; Gustavsson et al., 2017; Rüter et al., 2016; Taeroe et al., 2017) tend to conclude that management of forests for products maximises long-term mitigation. Those that exclude substitution on grounds of uncertainty or lack of data (Böttcher et al., 2018; Dooley & Stabinsky, 2018; Raymer et al., 2011) tend to be dominated by the loss of forest carbon associated with harvesting, and to conclude that reducing harvest and allowing forests to regenerate provides the greatest benefit to the climate.

> *"Studies that do quantify substitution tend to conclude that management of forests for products maximizes long-term mitigation."*

Differences in scale of the analysis and the timescale of interest also affect the recommendations (Vance, 2018). Forest modelling studies often consider a single stand, in which harvest causes a large and abrupt emission (a carbon debt) followed by a gradual regeneration. Yet over a landscape of different-aged stands, emissions and sequestration are more smoothly distributed over time (Vance, 2018). This in turn relates to the timescale chosen for analysis. Keith et al. (2015) suggest that the next few decades are the most relevant for preventing climate change, a view which favours short-term increases in forest carbon storage over reductions in cumulative emissions associated with long-term forest management. Such a policy choice significantly affects the optimum strategy in forestry.

FACTOR 2: THE FOREST AND MANAGEMENT SYSTEM UNDER CONSIDERATION

A second driver behind variation in conclusions is the diversity and variability in forestry systems across Europe. Typically, the most important determining factors are (i) the growth and sequestration rate of the managed forest compared to the baseline natural forest, (ii) the efficiency of wood harvest and product manufacture, (iii) the end products into which harvested wood is converted and (iv) any land use change or other large emission associated with the system. Emissions associated with fossil fuel or fertilizer use in forest management, harvesting, transport or wood product manufacture are generally small compared to the carbon contained in the forest and harvested wood (Berg & Karjalainen, 2003; De la Fuente et al., 2016), although this is less true of pulp and paper production (Dias et al., 2007).

Growth and sequestration rates

Wood harvest in a previously unmanaged forest always involves an immediate net emission of forest carbon, driven mainly by the decomposition or burning of forest residues, waste wood and any unharvested trees damaged by harvest (Keith et al., 2015).

Management for wood production, however, typically seeks to maintain forests in a phase of high growth in order to maximise net annual yield. In actively managed forests, silvicultural practices can also improve growth rates and survival of young trees, which in time can further enhance net sequestration rates (Duncker et al., 2012; Vance, 2018). On average, managed forests may therefore be able to maintain higher sequestration rates (although not carbon stocks) than unmanaged forest. This enhanced sequestration can mean that managed forests can maintain higher *annual* mitigation rates than unmanaged forest (provided harvested wood is converted efficiently to long-lived products), especially in comparison to older forests in which net growth has slowed.

Similarly, faster-growing forests are able to more quickly re-sequester carbon emitted through intensifying harvest (Guest et al., 2012) and produce higher volumes of wood per unit of carbon emitted, maximising relative substitution benefits. Intensifying harvest in slow-growing natural forest ecosystems would therefore have more muted net greenhouse gas benefits in the short term.

Efficiency of wood harvest and product manufacture

A second key sensitivity is the percentage of the biomass removed from the forest stand (by harvest or damage) that ultimately ends up in useful products. If only a small fraction of the biomass removed is merchantable timber, or is otherwise recovered for products, the emission of carbon per unit of useful wood produced is much greater (Keith et al., 2015; Putz et al., 2008), and the benefits of product storage and substitution are drowned out by carbon emissions. This factor is behind the opposed conclusions of recent studies of harvest in natural mixed forests in Australia (Keith et al., 2015) and comparable studies in managed forests of Northern Europe (Eriksson et al., 2011; Taeroe et al., 2017). However, the opposite extreme – maximum extraction of branch, foliage and root biomass, typically for energy – can negatively affect soil carbon, biodiversity, productivity and other ecological indicators, requiring a balance between management objectives (Repo et al., 2011; Thiffault et al., 2011; Verkerk et al., 2011). Once harvested, climate benefits are maximised through efficient conversion of logs into useful products, as well as maximum utilisation of the harvested biomass.

End products

The final use of harvested wood determines both the duration of carbon storage in products and, crucially, the potential benefits obtained through substitution. Wood harvested for high-value, long-lived products such as construction wood tend to be both longer-lived than lower-value uses such as pulp or chipboard, and to act as substitutes for high-emitting alternatives such as concrete and steel (Kilpeläinen et al., 2016; Leskinen et al., 2018). Short-lived products, especially paper products, can make more efficient use of harvested wood, but re-emit carbon rapidly and carry a less clear substitution benefit (Dias et al., 2007; EPA, 2016; Kilpeläinen et al., 2013; Moberg et al., 2010). Use of wood and residues for bioenergy or biochar may or may not have greater benefits than leaving them in the forest, depending primarily on the counterfactual fate of biomass, the efficiency of energy conversion and the extent to which they truly displace fossil fuel use (Schlesinger, 2018; Ter-Mikaelian et al., 2015).

Land use change

Although relatively rare in Europe today[1], large-scale direct conversion of native forest or grasslands for plantations can drive significant emissions from standing biomass or soils, reducing any benefit for the climate on short timescales (Guo & Gifford, 2002; Liao et al., 2010; Vance, 2018). On the other hand, conversion of agricultural land to productive forest in response to some demand incentive can enhance forest carbon stocks on the landscape and accentuate the overall carbon benefit (Guo & Gifford, 2002).

Land use change is an important factor at the level of landscapes and economies as well as individual forest stands. Policies and market conditions affect the economic attractiveness of wood production, maintaining standing forest and other forms of land use. Such incentives can encourage landholders to convert public or private forest to other land uses (a net carbon loss) or to plant trees on unforested agricultural land (a net carbon gain) (Vance, 2018). High-value markets for wood products can provide one set of incentives to maintain and increase forest area, and any proposals to reduce wood harvest must offer alternative policies and incentives to avoid the loss of forest area and landscape carbon stocks (Dale et al., 2017; Vance, 2018). The role of such incentives goes beyond the realm of science and requires a clear understanding of the economic and policy context.

FACTOR 3: THE COUNTERFACTUAL AND WIDER CONTEXT

Any attempts to quantify net climate benefits of a policy or management regime, at the stand level or for a whole economy, must make an assumption about what would have occurred in the absence of this intervention (Keith et al., 2015; Parish et al., 2017). This determines the reference, or counterfactual, scenario. It is often assumed that the counterfactual to managing forest for wood is undisturbed forest that is allowed to regenerate naturally (Parish et al., 2017; Schlesinger, 2018; Sterman et al., 2018). However, counterfactuals in a given context may include conversion to other land uses, and cessation of management can also leave forests more vulnerable to disturbances (Vance, 2018). In some historically managed European forests, such as coppice, traditional management has become an integral part of the ecosystem, and lack of demand for wood could lead to abandonment and ecological degradation (Unrau et al., 2018).

The choice of reference scenario is especially critical for quantifying substitution, especially concerning the climate benefits of bioenergy. Where all harvested residue biomass is assumed to displace coal, with each megajoule (MJ) of energy obtained from biomass avoiding exactly one megajoule of coal combustion, maximum extraction of residues for energy often emerges as the most favourable scenario (Eriksson et al., 2011). Where natural gas or other less polluting fuels are assumed, or where each unit of bioenergy only partially displaces fossil fuels,

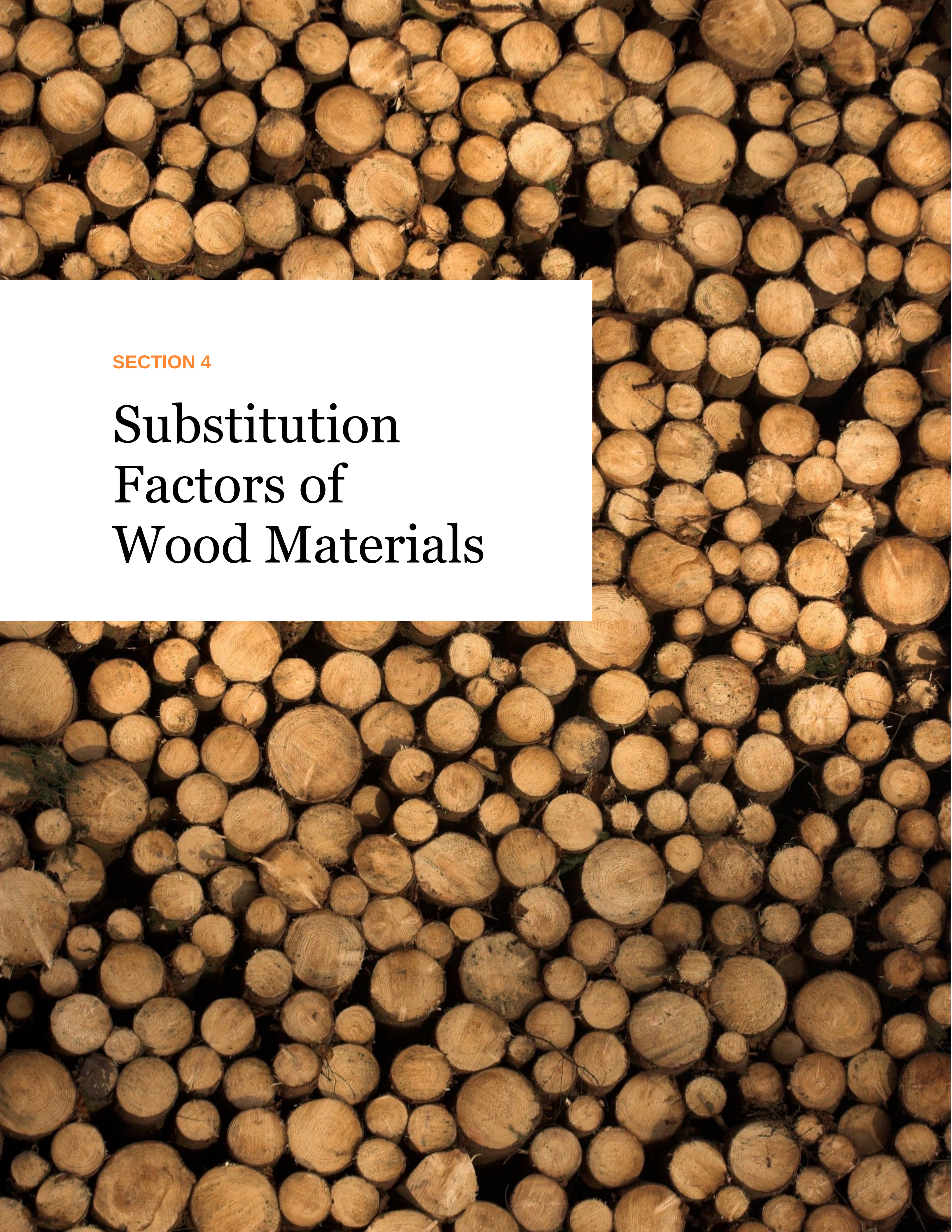
[1] While direct deforestation for plantations is relatively rare, there are examples of forest loss and degradation as a result of continued harvest of old-growth forest.

the benefits are much smaller and biomass extraction becomes less favoured (Eriksson et al., 2011; Ter-Mikaelian et al., 2015). Studies have suggested that the latter is more likely to be true at the level of an economy, with non-fossil energy sources on average displacing only one quarter of their equivalent in fossil energy use globally (York, 2012).

This problem is exacerbated when considering larger scales or timescales of analysis. Over the decadal to century timescales considered by forest policy, market conditions and technological factors, such as the background energy mix or carbon footprint of materials, will shift (Böttcher et al., 2018; Leskinen et al., 2018; Peñaloza et al., 2018), changing the relative value of substitution over time. Modelling scenarios of country- or Europe-wide forest management and wood product use, similarly, require many explicit or implicit assumptions about the future evolution of demand, land use pressures and technology (Böttcher et al., 2018; Rüter et al., 2016). Such assumptions are typically a matter of judgement rather than science and can generate conflicting policy recommendations.

SECTION 4

Substitution Factors of Wood Materials



Substitution Factors and Life Cycle Assessment

As shown in Section 3, the presence and degree of substitution effects is among the most influential drivers of climate outcomes from forest management. Quantifying such substitution benefits is the realm of comparative life cycle assessment (LCA), a formal method for comparing the life cycle environmental impacts of different products or materials fulfilling the same function in the economy. Comparative LCA studies of wood products or production systems typically assess the fossil energy consumption and emissions associated with the production of a wood product and one or more non-wood alternatives. Depending on the scope, they may also consider the use and disposal or recycling of the product (Leskinen et al., 2018).

From the relative climate change impacts, it is possible to derive a “substitution factor” describing “how much [fossil] GHG emissions would be avoided if a wood-based product is used instead of another product to provide the same function” (Leskinen et al., 2018). It is typically reported as a ratio between the amount of fossil carbon emission avoided and the amount of carbon contained in a wood product, in units of kgC / kgC. As defined by Leskinen et al. (2018), the concept excludes carbon stored in forests or products, but may include avoided fossil fuel use if harvest or manufacturing residues are burned for energy, or if the product itself is burned for energy at the end of its life.

> *“It is possible to derive a ‘substitution factor’ describing ‘how much [fossil] GHG emissions would be avoided if a wood-based product is used instead of another product.”*
>
> – Leskinen et al. (2018)

For example, consider a wooden construction material that has an estimated substitution factor of 1.5 kg C / kg C. This indicates that the use of this material in place of the expected alternative (e.g. concrete) would result in a net reduction in *fossil* greenhouse gas emissions across the whole building life cycle of 1.5 kg of carbon for every kilogram of *biogenic* carbon contained in the wooden material. Put differently, for every 1 kg of carbon contained in the wood product used in a building, 1.5 kg less carbon is emitted in producing, using and disposing of that wood product than would be emitted in producing, using and disposing of the concrete alternative. Importantly, this is separate from any benefit associated with storing biogenic carbon in the product itself, or of maintaining or increasing forest cover.

LCA traditionally assumes that under sustainable forestry, carbon in managed forests is in steady state, and that carbon contained in biomass (“biogenic carbon”) can thus be considered climate-neutral (Tellnes et al., 2017). A growing number of approaches are being developed to include the dynamics of forest carbon more explicitly in LCA (Guest et al., 2012; Levasseur et al., 2013; Tellnes et al., 2017), and are becoming more widely used.

Substitution factors are valuable in characterising where wood products have the greatest potential to displace fossil emissions, but they must be used with caution. They typically derive from “attributional” LCA studies, which examine current, average, steady-state emissions associated with a product, or else from quantifying the marginal impact of a unit change in wood use (Skullestad et al., 2016). As such, there are a number of caveats that must be considered when using them to assess the impact of larger changes in demand within an economy (Plevin et al., 2014), or when projecting the value of substitution over time, when technologies and energy mixes will change (Leskinen et al., 2018).

Typical Substitution Factors for Major Wood Materials

The most comprehensive study of wood product substitution factors to date was published in 2018 by the European Forest Institute (Leskinen et al., 2018). This section reviews the main results of this synthesis and the wider life cycle assessment literature to summarise considers the state of knowledge in regard to substitution benefits. The study surveyed 433 substitution factor estimates across 51 studies, and concluded that, across the life cycle, the average substitution factor was +1.2 kgC per kgC in the wood product, meaning that for each kilogram of carbon in wood products that substitute non-wood products, an additional 1.2 kilograms of fossil carbon emissions are avoided.

The range of substitution factors across products and studies is wide, however, with 95% of values between -0.7 and +5.1 kgC per kgC (Leskinen et al., 2018). In some cases, especially for emerging products, there is genuine *uncertainty* in the process and emissions data associated with wood products and their alternatives; this will be reduced as better data are collected. However, Leskinen et al. (2018) report that the majority of the variation in substitution factor estimates is instead due to *variability* between products, between manufacturing processes and energy systems across Europe, between assumptions used in LCA studies and between the chosen scope and accounting framework used in each study. For those products that have been relatively well-characterised in the LCA literature, there may be more value in clearer interpretation and communication of the results, or in expanding the scope or scale of analysis, than in additional data collection.

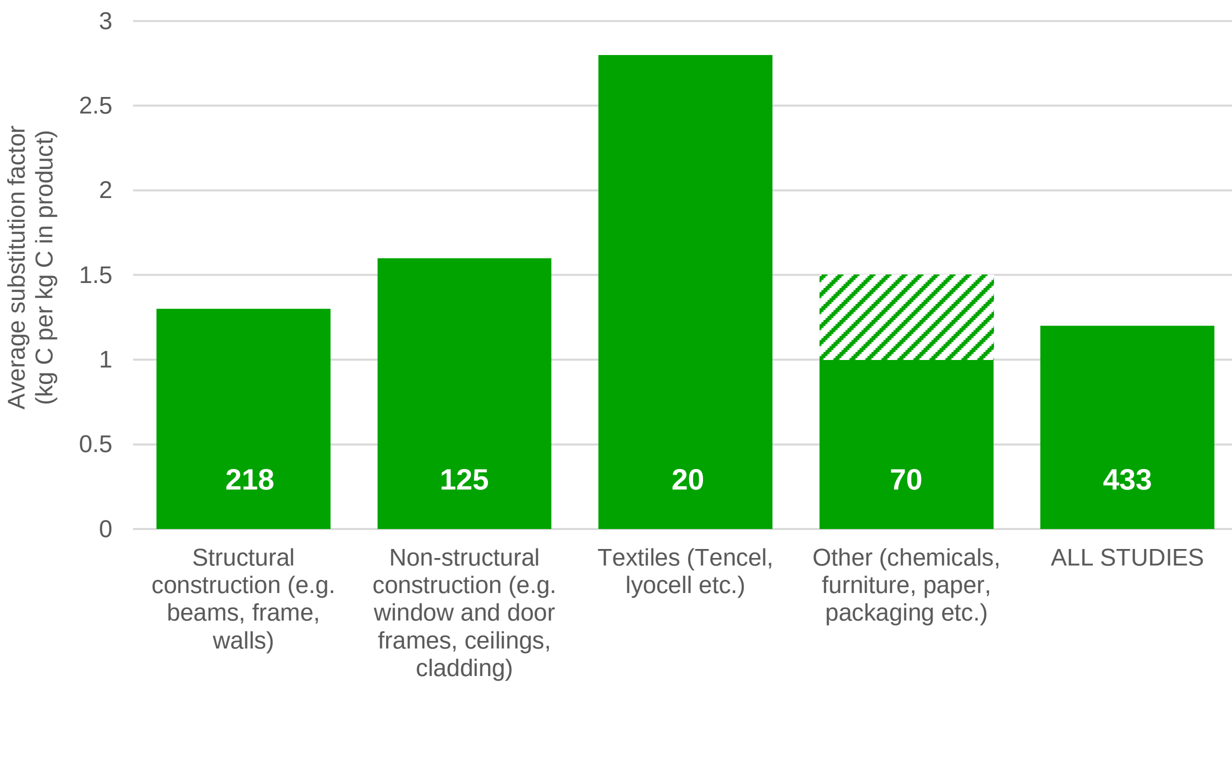
Aside from energy, the vast majority of studies of wood product substitution have focused on the construction sector (Leskinen et al., 2018). Wood as a structural material or for non-structural uses often displaces emissions-intensive alternatives such as concrete, steel, brick or aluminium, yet entails relatively low processing emissions (Sathre & O'Connor, 2010). There is thus robust evidence that the use of wood in construction, to the extent that it avoids the use of such alternatives, reliably reduces fossil fuel emissions across the economy (Leskinen et al., 2018). Substitution factors for construction wood are typically positive (a net emissions benefit), and average +1.3 kgC per kgC for structural uses and +1.6 kgC per kgC for non-structural uses such as door and window frames (Leskinen et al., 2018). The emergence of high-performing engineered wood products such as cross-laminated timber (CLT) has enhanced these prospects further, by opening up new opportunities to use wood in larger structures that would traditionally have required reinforced concrete (Ramage et al., 2017; Skullestad et al., 2016).

"There is robust evidence that the use of wood in construction, reliably reduces fossil fuel emissions across the economy."

There is far less research on substitution factors for short-lived product categories where wood-based materials are already widespread (e.g. graphic paper, packaging) or where new products using wood as a feedstock are starting to emerge (e.g. textiles and biochemicals) (Leskinen et al., 2018). The few studies that have explored the latter, especially emerging wood-based textiles such as Tencel and lyocell, have identified significant potential benefits in avoided fossil emissions relative to conventional alternatives (e.g. cotton or synthetic fabrics). Figure 4 reviews some substitution factors associated with different product categories.

Part of the reason behind the relative lack of data for some mainstream existing uses is the complexity of substitution effects relative to construction. For example, the main alternatives to graphic paper (newspapers, magazines, office paper etc.) are digital media. Greenhouse gas emissions associated with digital media and devices cannot be compared straightforwardly with those of paper, and depend enormously on assumptions about how the digital devices are being used (Bull & Kozak, 2014; Moberg et al., 2010). However, life cycle assessments of pulp and paper production do tend to find that fossil emissions per unit of product or input wood are high compared to other wood products (Dias et al., 2007; González-García et al., 2009).

FIGURE 4: BREAKDOWN OF AVERAGE SUBSTITUTION FACTORS REPORTED FOR DIFFERENT PRODUCT CATEGORIES, FROM LESKINEN ET AL. (2018). MOST MATERIALS ACHIEVE A SUBSTITUTION FACTOR (NET LIFECYCLE REDUCTION IN FOSSIL FUEL EMISSIONS) OF AT LEAST 1 KGC PER KGC IN THE WOOD PRODUCT UNDER TYPICAL USE SCENARIOS, WITH SOME USES (E.G. NON-STRUCTURAL CONSTRUCTION, TEXTILES) ACHIEVING EVEN GREATER REDUCTIONS. 75% OF DATA POINTS ARE RELATED TO CONSTRUCTION, WITH LIMITED RESEARCH ON OTHER PRODUCT CATEGORIES.



Packaging is a huge consumer of wood pulp and paper in Europe, and yet there is relatively little clear information on substitution factors attainable through substituting wood-based packaging for other forms of packaging (Leskinen et al., 2018). This is in part owing to a small number of studies, but also reflects the huge diversity of packaging and the complexity of environmental issues surrounding it. For a given packaging use, there are many alternative materials (Leskinen et al., 2018). In addition, for the case of food packaging, the environmental impact of the product itself is often greater than that of the packaging, making packaging that aids in food preservation (typically plastic, glass or metal) more suitable for reducing GHG impacts than paper (Roy et al., 2009; Verghese et al., 2015). Finally, re-use and recycling often plays a major role in the life cycle footprint of packaging materials, and assumed rates can significantly affect the outcome (Roy et al., 2009; Zabaniotou & Kassidi, 2003). The climate benefits of substitution in packaging, especially for food products, are thus significantly more variable in practise than for construction uses, and choice of packaging materials should be made on the basis of performance, capacity for reuse and recycling, and broader environmental footprint as well as lifecycle climate footprint.

Textiles, emerging bioplastics and biochemicals present promising, yet under-explored, possibilities for substitution. Only a fraction of materials and chemicals that can be derived from wood have been studied (Leskinen et al., 2018), but early evidence shows that at least some categories of chemicals and textiles could significantly reduce net fossil emissions if substituted by woody feedstocks.

Key messages:

A greater portion of Europes forests are managed for timber harvest than on any other continent. A long history of management has produced a great variety of management systems.

The area and wood volume of Europe's forests are rising, and European forests are currently a net carbon sink. However, the strength of this sink is weakening as Europe's forests age.

Carbon stored in wood products is also increasing, although the annual increase is only 10% of that stored in forests.

A consideration of substitution factors suggests that the substitution of wood products for alternatives may currently reduce net emissions by between 10 and 100 MtC/year.

Rates of forest carbon sequestration in managed forests vary between 0.5 tC/ha/year to 3-4 tC/ha/year.

Substitution is one of the most important factors determining whether management for forest products carries a net GHG benefit.

SECTION 5

Key Messages and Next Steps

The European Forest Sector

Forests in Europe are managed on a wide spectrum from intensive monoculture timber plantations to long-rotation harvest in even- or uneven-aged mixed forests. Carbon dynamics, wood production and management needs vary considerably across this spectrum, and this must be accounted for in assessing future scenarios of European forestry.

The area and wood volume in Europe's forests are rising due to reforestation, silvicultural management and recovery from historic exploitation. It is possible to increase wood harvest in some European forests while maintaining and increasing overall wood volume and forest carbon stocks. However, any change of management in Europe's forests must be capable of balancing the roles of forests in protecting biodiversity, water and soil, as well as the forest carbon sink.

Climate Change Mitigation in European Forests

Forests in the European Union are currently a net sink of approximately 110 million tonnes of carbon per year, most of which represents net increase in standing forest biomass. However, evidence suggests this sink is declining owing to the aging of Europe's forests, increasing land use and harvest pressures and natural disturbances.

A further 110 million tonnes of carbon is removed from forests each year by harvest for wood products, but the net increase in wood product storage is only 5-10% of this value due to corresponding emissions from decomposition or burning of harvested wood. It is much harder to calculate the benefit of substitution across Europe, since it depends on detailed knowledge of the counterfactual scenario of zero wood product use. But consideration of substitution factors suggest it may be between 10 and 100 MtC/year.

In addition to greenhouse gas benefits, forests also affect the climate through their influence on albedo, water cycling and atmospheric heat transport. In particular, any expansion of boreal forest or further shifts towards coniferous species are likely to lead to reduced albedo and regional warming impacts that could reduce or even outweigh any additional carbon sequestration. These complex dynamics must be considered in any coherent Europe-wide forest management strategy aiming to mitigate climate change.

Rates of forest carbon sequestration in managed forests vary across Europe and between forestry systems, ranging from about 0.5 tC/ha/year in boreal or dry Mediterranean forests to 3-4 tC/ha/year in western and central European forests. However, while fast-growing coniferous and exotic species tend to reach the highest productivities in terms of commercial timber volume, both coniferous and broadleaved forests can achieve high carbon sequestration rates.

Substitution is one of the most important factors determining whether management for forest products carries a net climate benefit. Studies that exclude the benefits of substitution tend to conclude that reducing wood harvest is the best way to minimize net GHG emissions at least in the short term. Conversely, where studies assume optimistic substitution scenarios in which wood displaces carbon-intensive alternatives such as steel, concrete or coal, substitution tends to outweigh forest carbon impacts and maximizing harvest is presented as the optimum outcome for the climate.

However, substitution benefits are highly sensitive to assumptions about the type, emissions footprint and amount of displaced materials or fuels. Forest stand- or product-level studies typically define scenarios where each unit of wood directly displaces a unit of alternative material or fuel, and often assume a best-case substitution scenario (e.g. with harvest residues displacing coal or natural gas). Where these assumptions do not hold, substitution may entail smaller benefits than reported.

Other key factors that affect the climate outcome of forestry are (i) the rate of forest growth and regrowth after harvest, (ii) the efficiency of wood harvest and manufacture of products, (iii) the type and lifetime of products and (iv) interactions between forest management, product markets and land use change (deforestation or reforestation). Rapid growth, high utilization of wood and long-lived products all increase the benefits of managed forestry, while slow regrowth, inefficient harvest and a predominance of short-lived products all reduce any benefit to the climate. Fossil fuel emissions associated with forestry and product manufacture are, with the exception of pulp and paper production, generally small compared to biogenic emissions.

Critically important to any estimate of the climate benefits of wood product use is the assumed reference or counterfactual scenario: what would have happened in the absence of a management or policy choice. This is especially important for substitution, where displacing emissions-intensive materials and energy sources such as steel or coal can carry several times the benefit of displacing a less polluting alternative. At the policy level, it is equally important to consider economic incentives that forest product markets apply to forests, and the implications for land use change and management that could come from changes in such markets.

Substitution Factors of Wood Materials

Substitution factors typical for products range from -0.6 to +5.1 kgC per kgC, depending on the product, manufacturing process, alternative material and the life cycle phases considered. Most wood products are associated with lower fossil carbon emissions than nonwood alternatives.

The evidence base is strongest for the benefits of using wood in construction as either a structural or non-structural material. Emerging construction materials such as cross-laminated timber, as well as growing production of textiles and chemicals from woody feedstocks, also hold great promise in reducing greenhouse gas emissions associated with conventional alternatives.

There is mixed and patchy evidence for the value of other short-lived products such as paper and packaging in substitution. Pulp and paper products, in particular, tend to be associated with higher fossil fuel emissions than solid wood products, and either have no clear substitution opportunity (e.g. graphic paper) or are complicated by multiple alternative materials, trade-offs in functionality and differences in end-of-life treatment.

Next Steps: Research and Action

This review has highlighted several areas in which further research or analytical work would be valuable in informing decision making. However, there are also several robust results from current research that indicate low-regret principles that European policymakers could begin incorporating into policy. Table 2 suggests an initial list of valuable next steps that could be pursued in each of these categories. Note that these relate primarily to reducing greenhouse gas emissions, and must be reconciled with other critically important environmental and social values and services provided by forests.

TABLE 2: SUGGESTED RESEARCH NEEDS AND POLICY PRINCIPLES BASED ON THIS INITIAL LITERATURE REVIEW.

Research and Analytical Needs	Low-Regret Policy Principles
Life cycle assessment of emerging wood-based products such as textiles, biochemicals and bioplastics.	Encourage the efficient and complete use of *harvested* residues and waste wood from manufacturing processes, except in cases where removal would impact biodiversity or soil condition.
Develop and disseminate tools and frameworks to clearly account for the climate impacts of forest growth, forest management, wood harvest and temporary carbon storage in product-level carbon footprint methodologies.	Promote re-use, recycling and cascading uses of wood products, and resource efficiency across all sectors.
Conduct country- or Europe-wide system modelling to characterise different alternative futures for Europe's forestry sector in the context of global markets, and to understand trade-offs between short-term and long-term mitigation.	Support the use of wood-based materials from sustainable forestry systems in long-lived applications such as construction
Economic research to understand the relationship between changes in European wood product demand and how forests are managed both inside and outside the region.	Expand protection of European forests with especially high biodiversity or valuable protective functions, as well as remaining intact forests.
Better understand the importance of biophysical effects in determining the net climate impacts of changing forests.	Support steps to sustainably enhance productivity in forests managed primarily for wood, including active or abandoned coppice forests.

Next Steps: Towards a New Framework for Decision Making

Forests hold unique potential to mitigate climate change through a combination of carbon sequestration in growing trees, long-term carbon storage and provision of wood-based products that can help reduce fossil fuel emissions in the economy. To inform climate policy, it is therefore important to take a holistic view that encompasses the forest, the product and the wider system. There is a huge opportunity to integrate this holistic perspective more deeply into decision-making on European forest policy.

To be practically relevant to Europe, it will also be essential to take account of the unique history and diversity of European forest systems, and their protective, recreational and cultural roles in societies across Europe, as well as their roles in wood production and climate protection.

“Substitution”, the role of forest products in avoiding the use of emissions-intensive alternatives, can be the most important factor in determining the net climate benefit of managed forestry. However, we must always be mindful that substitution is a property of the system and not an inherent benefit of the use of wood. As such, it is also the factor most sensitive to context and assumptions. It could be valuable to make those assumptions explicit for policymakers to more meaningfully compare the climate footprint of wood and non-wood products in a given context.

Beyond substitution factors, the size of a mitigation opportunity depends on other aspects such as forest carbon sequestration, the efficiency of wood utilization, the duration of carbon storage and the scale of a potential market. We therefore recommend developing more holistic and context-sensitive metrics and tools, which integrate such factors into decision making. Such a holistic framework must be designed to help policymakers prioritize the biggest opportunities while ensuring that substitution does not negatively impact forest health or climate change mitigation across the whole sector.

Principles for a new comparative framework for wood products:

1. **A holistic view of the forest, the product & the wider system is necessary to fully inform policy decision-making.**
2. **Recognise that substitution is a property of the system – from how the forest is managed to the processes to which the material is applied - and not an inherent benefit of the use of wood.**
3. **Integrate other key drivers of climate outcomes such as forest carbon sequestration, wood utilization efficiency and duration of carbon storage into metrics and tools.**
4. **Make assumptions and preconditions clear and explicit in any calculations.**
5. **Complement product-level metrics with larger-scale system modelling to articulate coherent scenarios for the future of the forest sector.**

One opportunity could be a framework focusing at the product level. For each product or material, we could seek to develop metrics for the whole-system climate impact that merge traditional lifecycle assessment/carbon footprint approaches with modelling and accounting for forest carbon, incorporating key conditions and explicit assumptions in the process. The final goal would be to reach a range of net climate and forest impact metrics, in terms of kg CO_2-equivalent per unit of product, that could be compared meaningfully with carbon footprints for non-wood materials in a given context.

Such product-level metrics and decision-making, however, must be supported by larger-scale system modelling of the European forest sector. Many important trends and dynamics in the forest sector cannot be quantified at the level of individual products. Economic and regional ecosystem models can be used to map out alternative future scenarios of the forest sector under different policies, in order to understand the relationships between markets, policies, climate and the changing condition and area of Europe's forests.

SECTION 6

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