Expanding productive forests creates cost effective carbon sinks and reduces loss of natural forests by offsetting timber extraction

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Contents

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Executive summary

1. It is widely accepted that the climate is changing with historic high temperatures, wildfires, and flooding experienced in many regions of the world. Climate change mitigation strategies require a major reduction in CO_2 entering the atmosphere (e.g. burning of fossil fuels, intensive agricultural systems, destruction of natural forests), and to reduce levels of CO_2 already in the atmosphere (carbon capture). **Expansion of productive forests remains one of the most effective strategies for removing and storing CO_2 from the atmosphere in addition to producing timber on a sustainable basis**.

2. **It is incumbent on developed nations as the biggest emitters of carbon to increase investment in climate change mitigation strategies that include expansion of their domestic productive forest areas.** Developed nations are also the biggest users of wood products (e.g. UK is the world's second biggest importer of wood products (second only to China) importing 81% of its requirements) and increasing domestic wood production would reduce the need for imports indirectly facilitating the reduction in damage and loss of the world's natural forests (a significant contributor to greenhouse gas (GHG) emissions) through timber extraction offsetting (i.e. using timber output from productive forests to reduce logging damage and loss of natural forests). Many European countries are revising down their production forecasts due to climate induced damage (particularly drought stress and insect attack) raising concerns over where future imports will come from and whether production is sustainable.

3. Despite the economic and environmental importance of productive forests throughout Europe and elsewhere in the world, future expansion of productive forests has come under sustained criticism from some environmental organisations and media outlets primarily over the use of non-native species and expansion oriented towards commercial production. **This report sets out why expanding productive forests is critical in terms of climate change mitigation and protection of natural forests through timber extraction offsetting.**

4. Wood is a highly versatile material, 'locks up' carbon in long-lived structures, and can be sustainably produced in perpetuity. Wood is **significantly more effective at embedding energy and has greater thermal insulation properties than alternative materials**. Replacing plastic packaging with wood-based products such as paper and cardboard contributes towards climate change mitigation and reducing pollution.

5. **Productive forests comprise only 3% of total global forest area yet produce one third of the world's industrial timber.** This is due to the combination of high productivity and focused activity in relatively small areas. This has the additional benefit of leaving a smaller 'environmental footprint' in comparison with the more expansive and damaging timber extraction from natural forests. Expansion of productive 'plantation' forests is not keeping pace with global timber demand with the shortfall increasingly sourced from natural and semi-natural forests that are already under severe pressure from human activity. **Productive forests yield over ten times more timber on an area basis than natural forests, therefore**

meeting the entire current global use of industrial timber would only require 0.3 to 0.6 billion hectares of productive forest, a fraction of what would be needed from natural forests.

6. While productive forest expansion has been taking place in many countries, limiting global warming to 1.5°C above pre-industrial levels (2016 Paris Climate Agreement) will require urgent mitigation strategies to be put in place including significantly increasing forest carbon sinks. Unlike environmental forests where there is little or no expectation of timber production, a significant part of greenhouse gas mitigation potential of productive forests involves locking up carbon in the harvested wood. When accounting for both forest growth and use of the wood, **productive forests support up to 269% more greenhouse gas mitigation potential than newly planted broadleaf conservation forests**.

7. Productive forests are also more cost effective as carbon sinks in comparison with 'technological' approaches to removing atmospheric carbon. **Costs of planting and managing productive forests as carbon sinks has been estimated at between £3 or £4.50 per tonne of CO_2 sequestered (harvested wood not included in study), whereas removing atmospheric carbon using carbon capture and storage (CCS) technology is estimated to cost a minimum of £50 per tonne of CO_2.**

8. While the use of non-native species in productive forests remains a focus of criticism among some environmental groups, the immediacy of the crisis surrounding climate change has emphasised the **need to use tree species in new afforestation programmes that show greater resilience to potentially less favourable climatic conditions in the future and possible threats from novel pests and diseases**.

9. New afforestation programmes should include a 'carbon capture index' indicating their climate change mitigation potential. Governments must ensure that productive tree planting is sufficiently incentivised to implement climate adaptation measures. **Financial aid for tree planting should be scaled with carbon capture potential to encourage tree planting with the optimum mitigation value**.

1. Introduction

Anthropogenic impact on the global environment is increasing pressure on governments to deal with two of the most urgent climate-related issues of our time; 1) the need to reduce CO_2 levels in the atmosphere and, 2) to end the destruction of the world's remaining natural forest ecosystems—a significant contributor to greenhouse gas (GHG) emissions in addition to a major loss of biodiversity. Productive ('plantation' or 'commercial') forests (where the management emphasis is on timber production) have a critical role in addressing these issues.

While productive forests are effective carbon sinks and produce timber on a sustainable basis in addition to providing a wide range of social and environmental benefits (e.g. Sejo and Botkin 1997, Pawson 2013, Barua et al. 2014), there has been increased hostility towards production forestry internationally with much of the criticism directed at the use of non-native species and forest expansion oriented towards commercial production.

Policy decisions associated with forest expansion are increasingly influenced by the paradigms of 're-wilding' (minimal/no human intervention unless at the early restoration stage leaving an area to nature as opposed to more active management) and 'nativeness' (use of species that arrived due to natural processes with no human intervention) with the general presumption that there will be limited if any timber production. Claims that native broadleaved woodland and rewilding are more effective in climate change mitigation than productive forests (e.g. Lewis et al. 2019) have been challenged by numerous studies showing that productive forests are significantly better at removing and storing atmospheric carbon than environmental tree planting (e.g. Cannell and Dewar 1995, Nijink 2010, Leskinen 2018, Forster et al. 2021). Productive forests will continue to deliver mitigation long into the future when environmental forests will have reached their peak capacity (Forster et al. 2021). Indeed, the growth potential of productive forests is likely to be maintained or even to increase as the climate changes highlighting the importance of these forests as significant carbon sinks (Jarvis and Linder 2007).

While there is an urgency to reduce CO_2 levels in the atmosphere associated with climate change, there is an equally pressing need to reduce carbon entering the atmosphere and a significant source is through deforestation (e.g. Stern 2007). Productive forests play a critical role in reducing forest loss through timber extraction offsetting based on the premise that the more productive forests meet world demand for wood, the less the need to log natural forests (Sejo and Botkin 1997). World demand for timber is rising at around 4% per year and this rate of increase will likely see a significant shift from a global wood surplus to a wood deficit that in turn will see an increase in logging in natural and semi-natural forests including many of the world's most threatened tropical forests (Sedjo and Botkin 1997, Indufor 2012, Barua et al. 2014).

The global area of primary forest has already decreased by over 80 million hectares since 1990 particularly through agricultural expansion but also logging for timber (FAO 2020a). If developed nations as the biggest users of wood products do not significantly increase domestic timber production, more will have to be imported and this raises the issue of where the wood should come from and whether it is from sustainable sources. Climate change has also brought into sharp focus the 'carbon footprint' of transporting timber over long distances and reinforces the argument for increasing domestic timber production.

Wood from countries actively involved in illegal logging of primary forests regularly finds its way into the international marketplace (e.g. Nellemann et al. 2018). While forest certification is widely acknowledged for its positive impacts on sustainable forest management, most of world's certified forests are in developed countries (87% in Europe and North America) with limited uptake in developing countries making it difficult to control exploitation (Xu and Lu 2021). While illegal logging is usually associated with tropical zones, it is also occurring in temperate regions. For example, a recent investigation showed that 40% of wood sold to the European Union from Ukraine was illegally cut (Earthsight 2018).

Discussions based around environmental protection associated with nativeness and rewilding are generally easier to engage public interest and receive media coverage than those on providing raw materials even when it is as sustainable as wood, and this has seen an increase in public resistance to productive forestry. With increasing urgency associated with limiting the impact of climate change and ongoing destruction of natural forests, it is important that both domestic and global environmental benefits of productive forestry are better represented.

This report highlights the environmental benefits of wood as a carbon store and its energy efficiency in comparison with alternative materials. It then examines the role of productive forests in offsetting timber extraction from endangered natural forests. It also challenges the view favouring environmental tree planting, often supported by government aid, based erroneously on the premise that climate change mitigation potential is superior relative to productive forestry.

This report does not advocate one type of forest but presents arguments that crucial policy goals of climate change mitigation and protection of world's natural forests are best met through a planned and managed programme of productive forest expansion. Conclusions from this report although primarily focused on Europe have wider relevance elsewhere in the world.

2. Environmental benefits of wood

Increasing demand is partly driven by environmental pressures to replace polluting or non-sustainable materials with wood products. Wood is an excellent versatile, renewable material that is environmentally superior to most other alternatives (Building Research Establishment 2007). Arguments around carbon and 'embedded energy' are increasingly used to support the greater use of wood. For example, sawn timber for construction uses less energy in its production than cement (5×), glass (14×), steel (24×), brick (35×), and aluminium (126×) (from Koch 1992, Buchanan and Levine 1999). The thermal insulation properties of wood are better than concrete (5x), brick (10x), and steel (350x).

Coniferous wood (softwood) is preferred over broadleaved wood (hardwood) due to its lightness and high strength to weight ratio making it very suitable for construction. The construction industry is gradually acknowledging the environmental values of wood and architects and builders are increasingly engaged in using more wood products in construction as part of climate change mitigation strategies to 'lock up' carbon in long-lived structures (FAO 2016). As well as being energy-efficient, these buildings can be constructed using wood in both sawn and engineered forms (e.g. cross-laminated timber) where wood is made into wall panels or large beams to create homes, business premises, and leisure facilities with light open spaces (Wilson 2007).

Research has shown that a reduction in carbon emissions by substituting timber for masonry and concrete in building construction is around 20% and 60% respectively (Spear et al. 2019).

Wood-based products such as paper and cardboard are increasingly replacing plastic packaging that not only has climate mitigation benefits but also reduces pollution (Hurmekoski et al. 2018). Advances in the production of biochemicals from wood allow potential substitution of oil-based products including textiles where wood-based fibres such as viscose result in lower levels of CO_2 emissions than the production of cotton or synthetic fibres (Rüter et al 2016).

The substitution benefits of using wood to replace alternative non-wood products are mainly gained from reduced fossil GHG emissions during the production stage of wood products (Leskinen et al. 2018). Demand for wood products is also expected to grow driven by concerns over the impact of plastics and other polluting materials on the environment and the impact of climate change. While the environmental advantages of using wood products are widely acknowledged, where our wood comes from is often poorly appreciated.

3. Environmental impact of trade in wood products

High importing countries may find continuation of supplies under threat. For example, many European countries are revising down their production forecasts due to climate induced damage primarily through a combination of drought stress and insect attack (Forest Europe 2020). This will inevitably impact on timber availability from European exports and will raise environmental concerns about where imported wood is sourced in the future. Furthermore, Russia intends to stop exporting softwood logs from the east of the country placing greater pressure on China's extensive wood processing sector. China as the biggest global importer of wood products will have to replace this supply of timber from elsewhere in the world and Europe is one potential source placing further pressures on international timber availability.

One third of global industrial timber comes from productive plantation forests, yet they comprise only 3% of the total global forest area (FAO 2020b). While plantation forests continue to expand, this is not at a level sufficient to keep pace with global timber demand, which will have more than doubled by 2050. Productive plantation forests, based on current levels of expansion, are predicted to supply *less than one quarter of world demand by the middle of this century* with the shortfall increasingly sourced from natural and semi-natural forests (Indufor 2012).

By not expanding production in a geographical area such as the EU will almost certainly result in increased production elsewhere in the world to meet demand (Leskinen et al. 2018). Many of the world's natural and semi-natural forests are already under severe pressure from human activity. With increasing international demand for timber inevitably pushing up prices, an increase in illegal logging is predicted resulting in forests particularly in tropical and semi-tropical regions being unable to sustain increased production targets due to unsustainable timber extraction (Barua et al. 2014).

The need to protect the world's remaining natural and semi-natural forests is widely acknowledged and moves the debate back to the role of productive planted forests that combine high productivity and focused activity in relatively small areas leaving a smaller 'environmental footprint' in comparison with the more expansive and damaging timber extraction from natural forests (Barua et al. 2014). Natural forests produce relatively low volumes of usable timber ranging from about 1-3 cubic metres per hectare annually (Sedjo and Botkin 1997) with the result that expansive areas of forest need to be logged to achieve an economic timber output that in turn causes significant environmental damage in extracting the timber (Barua et al. 2014).

Annual global use of industrial timber is estimated at around six billion cubic metres, a volume that would require 2-6 billion hectares of natural forest to achieve and, given that the global area of natural forest is estimated around 3.75 billion hectares (FAO 2020b), *producing timber at the current level of demand would likely exceed all the world's remaining natural forests to supply*. By contrast, productive forests readily produce at least ten and up to 20 cubic metres per hectare per year (higher yields are not uncommon) (Sedjo and Botkin 1997), and this would require only 0.3 to 0.6 billion hectares of productive forest to meet the entire current global use of industrial timber, a fraction of what would be needed from natural forests.

Meeting future global roundwood demand without additional logging in natural forests will require a major expansion of productive forests well beyond current levels (current global area of productive planted forest ~124 million hectares—FAO 2020b). This would not only meet more of world demand; it would also allow most of remaining natural forests to be devoted to wildlife protection and habitat conservation (Sedjo and Botkin 1997).

4. Forests and greenhouse gas mitigation

Planting trees is not the 'ideal' or only solution to reducing atmospheric CO_2 levels, nor is it a substitute for reducing fossil fuel use; nevertheless, forests are a critical part of a wider strategy in addressing the challenge of climate change. It is estimated that total global carbon stocks in forests decreased from 668 gigatonnes in 1990 to 662 gigatonnes in 2020 (FAO 2020b). While there has been an increase in tree planting in many countries in recent years, limiting global warming to 1.5°C above pre-industrial levels (Paris Climate Agreement of 2016) will urgently require mitigation strategies put in place including significantly increasing forest carbon sinks (Grassi et al. 2017). A recent report by the Intergovernmental Panel on Climate Change (IPCC 2019) recommended an increase of one billion hectares of forest to limit global warming to 1.5°C by 2050.

Around 90% of the carbon in forests is stored in the living biomass and soil organic matter with the remainder in litter and dead wood. The point at which newly planted productive forests maximise carbon sequestration potential is surprisingly rapid. Productive species achieve maximum absorption of incoming solar radiation and therefore carbon capture potential at canopy closure, which for average yielding spruce (14 cubic metres per hectare per year) can be approximately between 12 and 16 years old from planting (Jarvis and Linder 2007). At harvesting, soil carbon stocks (and a considerable amount of nutrients) can be replenished if most of the residues (e.g. branches, offcuts, tree stumps) are retained on site (Jarvis and Linder 2007).

Unlike environmental forests where there is little or no expectation of timber production, a significant part of greenhouse gas mitigation potential of productive forests involves the fate of the harvested wood defined by four life cycle stages (production, use, cascading [reuse] and end of life) (Leskinen et al. 2018). Accounting for both the forest growth and use of the harvested wood, a recent study based on these life cycle stages over a 100-year time horizon found that newly planted productive Sitka spruce (*Picea sitchensis* [Bong.] Carr.) forest over two harvests supported up to *269% more* *greenhouse gas mitigation potential than newly planted broadleaf conservation forests* and 17% more than newly planted fast-growing conifer forest left unharvested (Forster et al. 2021).

Substitution benefits are largely gained due to reduced emissions during the production and end-of-life stages, particularly when post-use wood is recovered for say energy. High productivity has the greatest influence on greenhouse gas mitigation (Doelman et al. 2020, Forster et al. 2021) and is consistent with other studies indicating that expansion of the forest area using fast-growing species is the most cost-effective way to sequester carbon (e.g. Stern 2007, Nijnik 2010).

The cost-effectiveness of productive forests as carbon sinks was highlighted in a study where costs of planting and managing productive forest were estimated at between £3 or £4.50 per tonne of CO_2 sequestered (harvested wood not included) depending on optimistic or pessimistic calculations respectively, whereas removing atmospheric carbon using carbon capture and storage (CCS) technology (while still a necessary part of carbon capture strategies) was estimated to cost a minimum of £50 per tonne of CO_2 (Openshaw 2016).

5. Why are non-native tree species important?

While the use of non-native species continues to be criticised with the implication of poor species diversity, there are numerous studies demonstrating that productive forests of non-native temperate trees are as biodiverse as forests of native species (e.g. Humphrey et al. 2000, Sax et al. 2004, Smith et al. 2008, Quine and Humphrey 2010, Irwin et al. 2014), and over time well managed productive forests can take on certain characteristics of 'old-growth' forests (Oliver and Larson 1996). The immediacy of climate change has renewed the debate on appropriate tree species to use in productive forests, with potential susceptibility to more severe climatic events and novel pests and diseases. Given their long life cycles, trees planted at the present time will still be alive in a future environment that is likely to be more challenging than at present and has highlighted the need for a greater range of more resilient species to be used and the establishment of species mixtures (e.g. Pretzsch 2009, Mason and Connolly 2013, Cameron 2015, Isbell et al. 2015, Pretzsch et al. 2017).

Arguments supporting the use of mixtures in productive forest stands is based on the likelihood of one of the species in a mixture surviving climate related damage (biotic and abiotic) limiting the potential economic loss if only a single species were present (Cameron 2015). The diversification of species in productive forests is already taking place in parts of Germany where pure Norway spruce (*Picea abies* (L.) Karst.) forests are being converted into mixed stands by introducing more drought tolerant Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Spathelf et al. 2009).

While native species have an advantage of a long history of inherited adaptation to their environment, they can in some circumstances be more vulnerable to environmental damage than introduced species (Battipaglia et al. 2009). Maintaining current species composition of native woodlands may no longer be possible because some native species of flora and fauna may not survive due to the inability to adapt quickly enough to the rapidly changing environment. This is not a reason to stop the restoration and expansion of endangered native forests; however, it must be recognised that *dealing with the imminent environmental crisis associated with climate change will require new thinking regarding future afforestation*. Use of non-native species well adapted to the forest site is an important part of adaptive forest management given an uncertain future climate and concerns over future threats to forest trees from pests and diseases (e.g. Spathelf 1997; Johann 2006).

6. Where should expansion of productive forests take place?

Studies carried out around in the world show that expansion of productive forests should primarily take place on marginal farmland or otherwise degraded land where there is the potential of high timber production value on land poorly suited for agriculture (e.g. Sedjo and Botkin 1997). Better integrating forestry with agriculture could also deliver productive areas of forest economically supporting the agricultural side of the business.

The need to create areas within productive forests that are left unharvested such as riparian zones remain a central feature of sustainable forest management. *Productive forests provide many ecosystem services including natural flood mitigation*, a role that needs to be better recognised given the increase in the incidents of severe flooding.

7. Conclusions

It is now widely accepted that climate change is taking place with historic high temperatures, wildfires, and flooding being experienced in many regions of the world. Climate change mitigation strategies require a major reduction in CO_2 entering the atmosphere (e.g. burning of fossil fuels, intensive agricultural systems, destruction of natural forests), and to reduce the levels of CO_2 already in the atmosphere (carbon capture). This report focuses on the role of productive forests as a key part of the strategy to sequester CO_2 from the atmosphere and reduce CO_2 emissions through the loss of the world's remaining natural forests through timber extraction offsetting. It presents evidence to show that productive forests are a cost-effective way of sequestering atmospheric carbon through a combination of higher productivity and the use of harvested wood.

Loss of natural forests particularly in tropical and semi-tropical regions is a significant contributor to GHG emissions in addition to a catastrophic loss of biodiversity. This report demonstrates that the global supply of industrial timber from productive forests could be achieved from a comparatively small area of global forest cover and in turn remove the economic pressure to continue logging endangered natural and semi-natural forests.

Discussions on productive and environmental tree planting are too often presented as competing options, but both have a place in our landscapes. Concerns about the environmental status of productive forests are often misplaced and evidence presented in this report shows that productive forests of non-native species have levels of biodiversity at least equivalent to native species. While rewilding may have an appeal of leaving areas of forest to nature, active management and periodic harvesting reduce the risk of environmental damage and safeguard carbon stocks within wood products while climate change increases environmental risks to old unmanaged forests (Forster et al. 2021).

The scale of forest expansion promised by many governments will require significant investment, and establishing trees is not cheap. If forest expansion is primarily based on native broadleaved species without any realistic economic return, then large-scale tree planting programmes as part of climate change mitigation strategies will not happen without a substantial input of taxpayers' money and this may not be so readily available with many competing demands to address. Politicians and society at large must face the reality that achieving significant forest expansion targets will require major investment from the commercial sector into productive forests.

The long planning horizons associated with forestry require a proactive rather than reactive adaptation in forest expansion and management. Evidence presented in this report suggests that if the world is to make a significant impact on climate change mitigation and protecting natural forest through timber extraction offsetting, greater emphasis on productive tree planting is needed.

8. Recommendations

1. Significant expansion of productive forests should be a central part of government strategies towards achieving climate change mitigation targets. Productive forest expansion should be primarily targeted towards degraded land that is poorly suited for agriculture or otherwise degraded. Protecting and expanding existing native forest areas should remain a priority.

2. Given the immediacy of the climate crisis, opportunities for new productive planting must not be delayed through overly administrative processes. Approval should be based on the premise of why productive tree planting *cannot* take place rather than introducing obstacles for the commercial sector to justify their proposal.

3. All new afforestation programmes should include a ‘carbon capture index’ demonstrating their climate change mitigation potential. This would provide governments, policy makers, and public a measure of the value of ‘green investments’ towards the goal of reducing atmospheric carbon.

4. Governments and society need to appreciate that if we grow more of our own wood, we will need to import less with the potential to offset timber extraction from endangered natural and semi-natural forests in addition to limiting the ‘carbon footprint’ of transporting wood products over long distances.

5. Governments must ensure that productive tree planting is sufficiently incentivised to implement climate adaptation measures. Financial aid should be scaled with carbon capture potential to encourage tree planting with the optimum mitigation value.

References

Battipaglia G, Saurer M, Cherubini P, Siegwolf RTW, Cotrufo MF (2009) Tree rings indicate different drought resistance of a native (*Abies alba* Mill.) and a non-native (*Picea abies* (L.) Karst.) species co-occurring at a dry site in Southern Italy. *Forest Ecology and Management* 257: 820-828.

Barua S K, Lehtonen P and Pahkasalo T (2014) Plantation vision: potentials, challenges and policy options for global industrial forest plantation development. *International Forestry Review* 16: 117-127.

Buchanan AH, Levine SB (1999) Wood-based materials and atmospheric carbon emissions. *Environmental Science and Policy* 2: 427-437.

Building Research Establishment (2007) Adding value to home-grown timber. Published by Scottish Forest Industries Cluster, Edinburgh.

Cannell MGR, Dewar RC (1995) The carbon sink provided by plantation forests and their products in Britain. *Forestry* 68: 35-48.

Cameron AD (2015) Building resilience into Sitka spruce (*Picea sitchensis* [Bong.] Carr.) forests in Scotland in response to the threat of climate change. *Forests* 6: 398-415.

Doelman JC, Stehfest E, DP, Tabeau A, Hof AF, Braakhekke MC, Gernaat DEHJ, van den Berg M, van Zeist W-J, Daioglou V, Meijl H, Lucas PL (2020) Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Global Climate Biology* 26: 1576-1591.

Earthsight (2018) Complicit in Corruption: How billion-dollar firms and European governments are failing Ukraine's forests. Report by Earthsight, www.earthsight.org.

FAO (2016) *Forestry for a Low-Carbon Future: Integrating Forests and Wood Products Into Climate Change Strategies*. Food & Agricultural Organisation of the United Nations, Forestry Paper 177, Rome, Italy.

FAO (2020a) *State of the World's Forests*. Food & Agricultural Organisation of the United Nations, Rome.

FAO (2020b) *Global Forest Resources Assessment*. Food & Agricultural Organisation of the United Nations, Rome.

Forest Europe (2020) State of Europe's Forests. Ministerial Conference on the Protection of Forests in Europe - FOREST EUROPE, Liaison Unit Bratislava. www.foresteurope.org

Forster EJ, Healey JR, Dymond C, Styles D (2021) Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nature Communications 12: 3831. https://doi.org/10.1038/s41467-021-24084-x

Grassi G, House J, Dentener F, Federici S, den Elzen M, Penman J (2017) The key role of forests in meeting climate targets requires science for credible mitigation Nature Climate Change 7: 220-226.

Humphrey JW, Newton AC, Peace AJ, Holden E (2000) The importance of conifer plantations in northern Britain as a habitat for native fungi. *Biological Conservation* 96: 241-252.

Hurmekoski E, Jonsson R, Korhonen J, Jänis J, Mäkinen M, Leskinen P, Hetemäki L (2018) Diversification of the forest industries: Role of new wood-based products. *Canadian Journal of Forest Research* 48: 1417-1432.

Indufor (2012) *Strategic review of the future of forest plantations in the world.* Study for the Forestry Stewardship Council (FSC), Bonn, Germany.

IPCC (2019) *An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways*. Intergovernmental Panel on Climate Change.

Irwin S, Pedley SM, Coote L, Dietzsche AC, Wilson MW, Oxbrough A, Sweeney O, Moore KM, Martin R, Kelly DL, Mitchell FJG, Kelly TC, O'Halloran J (2014) The value of plantation forest for plant, invertebrate and bird diversity and the potential for cross-taxon surrogacy. *Biodiversity and Conservation* 23: 694-714.

Isbell F, Craven D, Connolly J, Loreau M, Schmid B, Beierkuhnlein C, Eisenhauer N (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526: 574–577.

Jarvis PG, Linder S (2007). Forests remove carbon dioxide for the atmosphere: spruce forest tales! In Forestry and Climate Change, Freer-Smith PH, Broadmeadow MSJ, Lynch JM (Eds), CABI, Wallingford.

Johann E (2006) Historical development of nature-based forestry in Central Europe. In: Diaci, J. (ed) Nature-based forestry in Central Europe: alternatives to industrial forestry and strict preservation. *Studia Forestalia Slovenica* 126: 1-17.

Koch P (1992) Wood versus non-wood materials in U.S.A. residential construction. Some energy-related global implications. *Forest Products Journal* 42: 31-42.

Leskinen P, Cardellini G, González-García S, Hurmekoski E, Sathre R, Seppälä J, Smyth C, Stern T, Verkerk PJ (2018) *Substitution effects of wood-based products in climate change mitigation*. From Science to Policy 7. European Forest Institute. https://doi.org/10.36333/fs07

Lewis SL, Wheeler CE, Mitchard ETA, Koch A (2019) Restoring natural forests is the best way to remove atmospheric carbon. *Nature* 568: 25–28.

Mason WL, Connolly T (2018) Nursing mixtures can enhance long-term productivity of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands on nutrient-poor soils. *Forestry* 91: 165–176.

Nellemann C, Henriksen R, Pravettoni R, Stewart D, Kotsovou M, Schlingemann MAj, Shaw M, Reitano T (2018) *World atlas of illicit flows*. Global Initiative. www.rhipto.org www.interpol.int.

Nijnik M (2010). Carbon capture and storage in forests. The Royal Society of Chemistry, Cambridge. In: Hester R.E. and Harrison R.M. (eds.) *Carbon Capture: Sequestration and Storage, Issues in Environmental Science and Technology* 29: 203-238.

Oliver CD, Larson BC (1996) *Forest stand dynamics*. John Wiley & Sons, New York.

Openshaw K (2016) Carbon capture and storage in Scotland: potential for woody biomass. *Scottish Forestry* 70: 15-22.

Pawson SM, Brin A, Brockerhoff EG, Lamb D, Payn TW, Paquette A, Parrotta JA (2013) Plantation forests, climate change and biodiversity. *Biodiversity and Conservation* 22: 1203-1227.

Pretzsch H (2009) *Forest dynamics, growth and yield: from measurement to model*. Springer, Berlin.

Pretzsch H, Forrester DI, Bauhus J (2017) *Mixed-species forests: ecology and management*. Springer, Berlin.

Rüter S, Werner F, Forsell N, Prins C, Vial E, Levet AL (2016) *ClimWood2030, Climate benefits of material substitution by forest biomass and harvested wood products*. Perspective 2030 - Final Report, Braunschweig.

Quine CP, Humphrey JW. (2010) Plantations of exotic species in Britain: irrelevant for biodiversity or novel habitat for native species? *Biodiversity and Conservation* 19: 1503-1512.

Sax DF, Kinlan BP, Smith KF (2004) A conceptual framework for comparing species assemblages in native and exotic habitats. *Oikos* 108: 457-464.

Sedjo R, Botkin D (1997) Using forest plantations to spare natural forests. *Environment* 39: 14-20, 30.

Smith GF, Gittings T, Wilson M, French L, Oxbrough A, O'Donoghue S, JO'Halloran J, Kelly DL, Mitchell FJG, Kelly T, Iremonger S, McKee A-M, Giller P (2008) Identifying practical indicators of biodiversity for stand level management of plantation forests. *Biodiversity and Conservation* 17: 991-1015.

Spathelf P (1997) Seminatural silviculture in southwest Germany. *Forestry Chronicle* 73: 715-722.

Spathelf P (2009) *Sustainable Forest Management in a Changing World: a European Perspective*. (Managing Forest Ecosystems, Vol 19). Springer, Netherlands.

Spear M, Hill C, Norton A, Price C (2019) *Wood in Construction in the UK: An Analysis of Carbon Abatement Potential*. Report commissioned for the Committee on Climate Change, Ref BC-1383-2018-ES.

Stern N (2007) *The economics of climate change: The Stern Review.* Cambridge University Press, Cambridge.

Wilson P (2007) New timber Architecture in Scotland. Arcamedia, Edinburgh.

Xu L, Lu AJ (2021) Forest certification in developing countries: current status and hindrances in its adoption with a macro-framework. *International Forestry Review* 23: 105-126.