Essay

Not peer-reviewed version

Climate-Smart Forestry: A Review of Approaches, Management Strategies, and Risk Mitigation

Gbenga Lawrence Alawode *

Posted Date: 19 June 2023

doi: 10.20944/preprints202306.1335.v1

Keywords: climate-smart forestry; forest resilience; adaptive forest management; climate change mitigation; SFM; bioeconomy

Essay

Climate-Smart Forestry: A Review of Approaches, Management Strategies, and Risk Mitigation

Alawode G. L.

Faculty of Science, Forestry and Technology, University of Eastern Finland, Joensuu, Finland

Abstract: This essay review explores the concept of climate-smart forestry as an approach to mitigating and adapting to climate change. It highlights the need for a holistic approach to forestry that considers regional differences and synergies between ecosystem services. The essay discusses various management strategies at different scales, including species selection, mixed species cultivation, and the promotion of the bioeconomy. It also examines the trade-offs and synergies between different forest uses and the effects of forest management on ecosystem services. Furthermore, the review addresses major abiotic and biotic damage risks to forests, such as wildfires, windstorms, and bark beetle attacks, and proposes risk management strategies. Lastly, the review delves into the management of peatland forests, discussing the role of drainage, the impact of ditch network maintenance, and the challenges of peat ash fertilization. Overall, the review provides valuable insights into climate-smart forestry and its potential to contribute to climate change mitigation and adaptation.

Keywords: climate-smart forestry; forest resilience; adaptive forest management; climate change mitigation; SFM; bioeconomy

---

CLIMATE-SMART FORESTRY APPROACH

After the industrial revolution, the rate of release of CO_2—the most crucial greenhouse gas—has increased tremendously and contributed significantly to climate warming. Due to the increase in human-accelerated climate warming, which has surpassed 1^0C over the pre-industrial level and rising at the rate of 0.2^0 per decade (IPCC, 2018), the Paris Agreement was signed in 2015 by 194 countries to keep the warming at around 1.5^0C and entered into force on 5 Oct 2016 (United Nations, 2020). Regional differences and country-specific problems thus permit governments to develop a framework to fulfil this commitment. For example, the European Green Deal was developed by the EU to ensure the realization of climate neutrality by the year 2050 (European Commission, 2019).

Forest trees can remove carbon from the atmosphere and store it within their system as biomass. As a result of these characteristics, the concept of Sustainable Forest Management (SFM) has been promoted by many countries as a way of removing CO_2 from the atmosphere and fulfilling their climate commitment. In terms of climate change mitigation, this approach sees the forest as a carbon sink (Hetemäki and Seppälä, 2022), which is a limited view of the contribution of forests to mitigating climate change. Therefore, there is the need for a holistic approach to how forestry contributes to climate change mitigation and adaptation while considering regional differences and increasing synergies between ecosystem services; hence, the Climate Smart Forestry approach is developing (Hetemäki and Seppälä, 2022).

Increasing forest resilience through adaptive forest management is one key component of CSF. Careful species selection based on species and site characteristics can improve the stability and adaptation of forests to climate change. For example, substituting broad leaves for conifers with reduced spacing on upwind areas will enhance windstorm resistance. Additionally, shifting from monoculture to mixed species cultivation, which is an active adaptation strategy promoted by Germany, will improve biodiversity, and help in adapting to the anticipated pressure poised by climate change. When mixed species cultivation is combined with a reduced rotation period, the forest becomes less susceptible to biotic and abiotic attacks such as pests and windstorms, respectively.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 June 2023 doi:10.20944/preprints202306.1335.v1

In the USA, the Family Forest Carbon was developed for family forest owners with small land areas to get compensation for conserving their forest. This has increased the commitment to carbon emission reduction while providing economic gain for forest owners simultaneously. In addition, forest owners with larger forest areas receive payment for forest conservation and carbon absorption through the Forest Carbon Offset program (Miller *et al.*, 2014).

Furthermore, forests sequestrate carbon and store it in their system as biomass throughout their lifetime. The promotion of the Bioeconomy, through the substitution of fossil energy and carbon-intensive materials for wood-based materials, can reduce carbon emission and provides long-term storage of CO_2. For example, substituting conventional building materials for mass timber can reduce construction phase emissions by about 70%. In addition, replacing steel with nanocellulose—a material that is lighter and stronger than steel—can further reduce the release of CO_2 into the environment, thereby mitigating climate change. The European Forestry Institute is actively promoting the Bioeconomy within Europe and spreading the initiative to other regions.

Different regions have differences in climatic conditions, social needs, and political terrain. As a result, no singular approach to climate-smart forest management. The strategy adoption should be based on the considerations of the environment and people's needs. Additionally, the overarching management objective and intervention time frame should be adequately considered before selecting the best that fulfil these criteria. For example, Europe's CSF approach could focus on increasing biobased products and reducing the risk of Bark Beatle infestation and tree damage through windstorms. Conversely, developing countries, like those in Africa and South America, with high deforestation and lower biotic disturbances, should focus on forest restoration through afforestation and reforestation programs.

POSSIBLE EFFECTS OF FOREST MANAGEMENT AND HARVESTING INTENSITY ON ECOSYSTEM SERVICES AND THEIR SYNERGIES/TRADE-OFFS

Forests provide different goods and services that are beneficial to humans. The benefits are often contradictory, resulting in trade-offs between alternative uses as the increasing use of one results in the loss of others. For example, increasing biodiversity conservation will affect the forest's harvesting intensity and recreational activities. Creating a synergy between alternative forest uses to address diverse needs within society has constantly been a subject of discussion among forestry stakeholders. To address this issue, different forest management approaches have been adopted. These approaches present different ways of managing the forest at the stand, management unit and regional levels for optimal production.

At the stand level, adopting even-aged forest management and maintenance of higher stocking over time increases growth, carbon sequestration, and ecosystem stocks (Kellomäki etal. 2019). However, in the long term, the ageing of trees through a prolonged rotation period can decrease carbon sequestration and susceptibility to pests and insect attacks, reducing the trees' economic value. Dead trees also play host to forest pests and increase their reproduction and growth, increasing the forest's fuel content and making it more prone to the forest fire.

In the boreal forest, natural forests are predominantly heterogeneous and composed of tree stands of diverse sizes, species, and age classes. This heterogeneous forest structure can be simplified through the application of even-aged forest management, but with a negative effect on the diversity of the forest (Sini, *et al.*, 2021). In Finland, the impact of harvesting intensity on forest-dependent species has been reduced through the shift from removing all trees, as practised in the clear-cut system, to a system of retaining some parts of structural diversity. Another Even-aged Forest management method is the retention of forestry. This involves keeping some old trees or small stands of trees during harvesting to improve structural diversity (Fedrowitz, *et al.*, 2014).

Alternatively, Uneven-age Forest management is a further step toward increasing structural diversity, as practised in Quebec, Canada. This is a silvicultural system where different classes within a stand result in natural regeneration and higher structural diversity than in the even-aged stand (Kellomki, *et al.*, 2019). Additionally, when wood production is not the principal purpose, it is a suitable alternative, especially in parks and recreational and scenic forests. Conversely, the success

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 June 2023 doi:10.20944/preprints202306.1335.v1

rate requires shade-tolerant species, e.g., in Finland, Spruce is the only shade-tolerant economic tree species.

Furthermore, the substitution of slow-growing species for fast-growing species is another stand-level management approach. In Nigeria, exotic tree species grow faster than native species. Increasing the use of Teak and Gmelina (the two most popular exotic tree species) in restoration can increase the growth rate and carbon sequestration. However, it can influence the availability of native species in the long run due to the invasive nature of these tree species.

One of the best management methods to satisfy the increasing demand for the diverse use of forests at the management level is the management strategy that adopts thinning from above. Adopting this strategy without being restricted to rotation forest management provides more ecosystem services and economic profitability (Diaz *et al.*, 2019). In contrast, adopting rotation forest management with below-ground thinning provided the lowest carbon stock, carbon balance and biodiversity indicators.

When the primary objective is to increase biodiversity at the regional level, increasing forest conservation area becomes beneficial management, at least within the short term. This will increase carbon stock and biodiversity through increasing deadwood materials that provide suitable habitats for saproxylic species (Pikkarainen *et al.*, unpublished). However, this is at the expense of wood production, and in the long term, the trees become prone to biotic and abiotic attacks and sequestrate less carbon due to ageing.

MAJOR ABIOTIC AND BIOTIC DAMAGE RISKS TO FORESTS AND FORESTRY AND POSSIBLE RISK MANAGEMENT STRATEGIES AT DIFFERENT SPATIAL AND TEMPORAL SCALES

The effect of climate change on forests can be direct or indirect. The growth condition of a forest can change in response to the change in precipitation, temperature and CO_2 concentrations. Alternatively, the effect can be indirect through the forest's different biotic and abiotic disturbances. The latter will be the subject of discussion.

In Europe, increasing summer drought and anomalous dry conditions have been predicted due to climate change, causing evapotranspiration to intensify (Venäläinen *et al.*, 2022). This will reduce forest growth through pest attacks and increase tree mortality and susceptibility of forests to wildfires. In the event of large-scale Forest fires, as observed in Canada, a large amount of CO_2 will be released into the atmosphere, increasing carbon concentration and affecting the vegetation. However, the effect of large-scale wildfires can be cushioned through the fragmentation of more expansive landscapes into smaller ones to minimize fire spread. The availability of fuel within the forest can be reduced through timely thinning and removal of excessive deadwood.

Furthermore, Europe's increasingly wet and warm winters are increasing the risk of forests to windstorms and heavy snow loading. An increase in growing stock and the reduction in soil frost duration—which gives additional support for trees during the windiest seasons— will increase the vulnerability of the forest to windstorms (Schelhaas et al. 2003). Increasing winter soil moisture will also reduce the firmness of tree roots in the soil and increase the susceptibility of forests to storms (Lehtonen *et al.*, 2019). Broadleaves with a significant height-to-diameter ratio and young Scots pine are particularly vulnerable to snow loading, which increase stem breaking, leaning, and bending of trees (Nykänen et al. 1997; Venäläinen *et al.*, 2022). Additionally, forest configuration can influence the vulnerability of the forest to wind and snow damage. An example is that planting shallow-rooted Norway Spruce in high-risk areas will increase future wind damage (Ikonen *et al,* 2020).

Therefore, selecting site-appropriate tree species will help reduce wind damage risks. Also, timely pre-commercial and commercial thinning will be handy in achieving the appropriate forest growing stock and reducing wind damage. By avoiding heavy thinning in windy areas, wind damage can be reduced through the availability of adequate growing stock to withstand windstorms.

Bark beetle attack has gained significance in Europe within the last 40years, with an increase of about 70% (Seidl et al. 2014). Severe wind damage to trees and the increasing drought caused by climate change has increased the availability of breeding materials and the growth of this beetle

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 June 2023 doi:10.20944/preprints202306.1335.v1

(Marini et al. 2017). Specifically, planting Norway Spruce (one of the most abundant tree species) on sites with high soil water holding capacity and increasing the growing stock has reinforced the growth (Hlásny *et al*. 2019; Jandl 2020). At a minimal population, bark beetle attacks only damaged trees; however, the attack is spread to healthy trees when the condition favours the increase in population and can result in economic loss through the collapse of the timber market, as witnessed in Czechia (Venäläinen *et al*., 2022). Thus, reducing the number of hosts through the removal of harvested and wind-damaged trees and the timely thinning and cutting of infested trees can reduce population growth.

Additionally, planting Norway Spruce in its natural range will increase tree vigour and reduce bark beetle attacks. Different ecological niches of tree species can be beneficial in reducing the spread of Bark beetle in mixed stands. The availability of host trees is reduced, and other species can play host to natural enemies. The economic loss can be reduced by lowering damaged trees and the availability of other uninfected economic tree species.

While bark beetle is a significant biotic damage risk in Europe, the increasing temperature is causing the abundance of other biotic damaging agents. Nun moth is a defoliator historically absent in Finland (Melin *et al*., 2020) due to the freezing winter, as the egg gets frozen at a temperature below -30^{0}C (Fält-Nardmann *et al*., 2018). The increasing warmer winter has favoured the tremendously increase since the 1990s (Melin *et al*., 2020). Also, snow duration and depth reduction have increased the severity of moose (*Alces alces*) damage on Birch and young Scots pine seedlings in Northern Europe (Herfindal *et al*. 2015; Venäläinen *et al*., 2022).

CLIMATE-SMART PEATLAND FOREST MANAGEMENT

Peatland is a wetland covering an estimated area of more than 400 million hectares in about 180 countries, equaling about 3 percent of the earth's surface. Most peatlands are in the boreal region (around 80%), where the extreme cold temperature and high-water table supports the accumulation of peats through the slow rate of organic matter decay. Although the coverage area is limited, they play a crucial role in climate processes as they store about one-third of global soil carbon (Page *et al*., 2022)

Several processes in peatlands involves carbon, including but not limited to atmospheric CO_2 exchange, CH_4 emission, and dissolved organic carbon (DOC) production and export. Peats are significant carbon storage as they sequester more CO_2 from the atmosphere than the entire world's forests. Conversely, peatlands also emit carbon and methane, and the emission levels depend on land use, temperature, and water level. Furthermore, the draining of peatlands for forestry and agricultural activities emits a significant amount of carbon and nitrous oxide. These contribute to the amount of GHG in the atmosphere, increasing intensity and climate change. Due to the high amount of carbon stored, degradation can release a large amount of carbon into the atmosphere; hence, the need for effective management to protect the carbon stored in this ecosystem.

Drainage is an essential practice in peatlands as it helps to increase the productivity of mires and wet mineral soils by increasing tree growth. For example, 25% of Finland's forest land is drained peatlands, representing 25% of annual stem volume increment. Ditch Network Maintenance (DNM) is a means of sustaining and improving drainage conditions and increasing tree production (Minkkinen *et al*., 2008; Päivänen and Hånell 2012). It can be done by cleaning existing ditches that have lost their water transportation ability or digging supplementary trenches between the old ones. This practice is common in Finland, where there is little or no first-time drainage of pristine peatlands (Päivänen and Hånell, 2012). However, DNM increases the risk of exporting soil sediments and nutrients into receiving water bodies, resulting in water pollution (Nieminen 2003, 2004; Nieminen *et al*., 2010). For example, DNM operations in Finland are estimated to increase soil sediments export from land by 50% and cause more than half of forestry-induced phosphorus export. It also promotes the exports of dissolved inorganic nitrogen, especially ammonium.

Peat ash fertilization has been shown to eliminate phosphorus deficiency in Scots pine (Hytönen *et al*., 2016). However, due to the low Potassium content, peat ash alone is not a suitable fertilizer for peatlands suffering from potassium deficiency–which is quite common in thick-peated drainage areas (Mandre *et al*. 2010). Thus, the best result of peat ash application can be obtained on thin-peated sites with trees suffering from Phosphorus deficiency but can get potassium from mineral soils below the peat. Unfortunately, these types of sites are scarce. Furthermore, wood ash is known to increase tree growth on peatlands drained for forestry and the influence has been reported to last up to 50 years or more (Huotari, 2012).

Forest harvesting and the draining of peatlands can alter several factors controlling the production, decomposition, and transport of dissolved organic carbon. For example, clearcutting removes the evapotranspiration of tree canopy, leading to a higher water table and increasing dissolved organic carbon export from the peatland (Nieminen et al. 2010). Also, clearcutting can aid vegetation succession with pioneer species, such as broad leaves. When this occurs, these pioneer species can produce higher quality substrate for microbes that do not support soil carbon accumulation, leading to increased carbon emission.

Alternatively, continuous cover forestry has been suggested as a better option for clearcutting. In continuous cover forestry, methods such as selective harvesting, nutrient regeneration and avoiding soil preparation can have less impact on soil carbon and nutrient level than clearcutting. The low water level is also maintained through high evapotranspiration, reducing dissolved organic carbon and nutrient leaching rather than clearcutting.

CONTRIBUTION OF FORESTS AND WOOD-BASED PRODUCTS TO CLIMATE CHANGE MITIGATION

Forests have diverse roles, but the roles of forests in mitigating climate change are increasingly crucial due to the critical need to limit climate change impact. There are complex and complementary relationships between forests and climate change. On the one hand, forests can mitigate climate change through carbon sequestration from the atmosphere and storage in forest biomass and soil. On the other hand, harvesting, deforestation and forest degradation can release stored carbon into the atmosphere, contributing to climate change (Kilpeläinen and Peltola, 2022).

Furthermore, protected areas have been seen as essential for conserving biodiversity and tools for adapting to the changing climate. Through the provision of abode and migration corridors, they support the adaptive capacity of species to climate change. Additionally, they protect people from sudden and extreme weather events such as droughts and flood, and indirectly, help economies by reducing climate-related negative impacts costs (FAO, 2022).

However, the contribution of the forest as a carbon sink is not uniform across the globe as it depends on the interplay between climatic and soil conditions, forest area and structure, the management intensity and the level of socioeconomic development. For example, forest productivity is higher in central Europe, where Broadleaved deciduous and mixed evergreen forests are more common than in other parts of Europe.

Wood-based products play critical roles in climate change mitigation. When forests are harvested, part of the carbon is released through the harvesting activities and soil disturbances, and a portion is stored in wood-based products. In addition to carbon storage in forest ecosystems and harvested wood products, using wood to replace more carbon-intensive materials and fossil fuels can be beneficial by reducing fossil greenhouse gas emissions from other sectors of the economy.

While the role of forests in climate change mitigation is well understood, the contribution of wood-based products is not. Therefore, combining the product-specific substitution factor with the quantity of wood product produced or consumed can give an estimated overall GHG substitution effect. A substitution factor refers to how much GHG will be avoided if another product is replaced by wood-based material for the same function. It is used to assess substitution impact of wood-based products by multiplying product volume by the corresponding substitution factor.

In several cases, using wood and wood-based materials is associated with lower fossil and processed-based emissions. It also provides long-term storage of carbon and prevents the release into the atmosphere, reducing the intensity of radiating energy and preventing climate change. Hence, substitution can benefit climate change mitigation by substituting products with higher GHG life cycle emissions for those with reduced GHG life cycle emissions. However, the substitution effect depends on the interplay between several factors, including, the type of wood product in consideration, the non-wood product to be substituted, the use of residues from harvesting, the shelf life and the overall life management (Pekka *et al.*, 2018). Also, the scale of production and consumption should be considered along with the substitution factor in measuring the comprehensive benefits. At the regional level, understanding market dynamics and a thorough substitution process are required to improve the substitution benefits.

Conclusion

One crucial component of CSF is increasing carbon sequestration and storage while maintaining other ecosystem services. Therefore, preference should be placed on management approaches that fulfil these objectives. Although no "best" climate-smart practice exists, emphasis should be on minimizing trade-offs, enhancing forest resilience, and increasing its capacity to supply goods and services in perpetuity. Additionally, the success of policies and strategies depends on acceptance within the society; hence, different stakeholders should be involved in decision-making process to increase acceptability and success rate.

Forest owners and managers should consider trade-offs between ecosystem services and adopt a management strategy with the highest synergy. Management strategies' spatial and temporal variation should be considered alongside the site-specific differences before selecting the best approach. While some are best within the short term (e.g., increasing forest conservation area), some can yield the best results in the long term. Consequently, adaptive forest management is a good strategy for reducing trade-offs and increasing synergies between ecosystem services.

The severity of climate change, adaptive capacity and sensitivity of the forest can influence its response to biotic and abiotic disturbances. While variations in the type and scale of occurrence vary, adaptive forest management can provide a way of responding effectively. The age structure and species composition of forests can be modified by mixing conifers and broadleaves tree species on a stand and selecting highly resilient species. This will reduce forest vulnerability and increase resilience after disturbance. Ultimately, no single management strategy can yield the best output due to the uncertainties in future climate change; hence, strategies and interventions should be adopted in tandem with the timespan and geographical considerations (Venäläinen *et al*., 2022).

The importance of peatland forests in regulating climate processes and mitigating climate change cannot be overstressed. However, applying effective management is key to increasing the productive potential of peatland forests while maintaining their climate-regulating functions. Climate-smart peatland forest management should avoid increasing and, wherever possible, limit human-induced GHG emissions from peatlands and maintain their carbon stores. This can be achieved by including carbon accounting in management planning and obtain information on the effect of management practices on climate change processes. Proper monitoring of carbon stored and greenhouse gas emissions from peatland forests will assist in acquiring knowledge on the effects of diverse management practices and the promotion of "best practice".

There are many uncertainties surrounding quantifying substitution benefits. Also, there is no single or straightforward way of analyzing the climatic benefits of substituting a biomaterial for a non-wood product. However, in achieving climate targets through substitution, overall benefits analysis should not only reflect historical or current situations. Future changes caused by anticipated increases in market shares of wood products, technological changes, new wood-based products, and the potential supplementary climate benefits should also be compared to the current state.

References

Ari Venäläinen, Kimmo Ruosteenoja, Ilari Lehtonen, Mikko Laapas, Olli-Pekka Tikkanen, and Heli Peltola. Climate Change, Impacts, Adaptation and Risk Management (2022). In Forest Bioeconomy and Climate Change, Managing Forest Ecosystems 42, https://doi.org/10.1007/978-3-030-99206-4_3

Ashton MS, Kelty MJ. The practice of silviculture: Applied Forest ecology.10th ed. Hoboken: Wiley; 2018.

Díaz-Yáñez O, Pukkala T, Packalen P, Peltola H (2019) Multi-functional comparison of different management strategies in boreal forests. Forestry *International Journal of Research* 93:84–95. https://doi.org/10.1093/forestry/cpz053

European Commission (EC) (2019) The European Green Deal. Brussels, 11.12.2019, COM(2019) 640 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

Fält-Nardmann JJ, Ruohomäki K, Tikkanen OP, Neuvonen S (2018) Cold hardiness of Lymantria monacha and L. dispar (Lepidoptera: Erebidae) eggs to extreme winter temperatures: implications for predicting climate change impacts. Ecol Entomol 43(4):422–430. https://doi.org/10.1111/een.12515

FAO (2022) The role of forest protected areas in adaptation to climate change. https://www.fao.org/3/i0670e/i0670e13.htm. Accessed on 17 Sept 2022.

Fedrowitz K, Koricheva J, Baker SC, Lindenmayer DB, Palik B, Rosenvald R, et al. (2014) Review: Can retention forestry help conserve biodiversity? A meta-analysis. J Appl Ecol. 2014;51(6):1669–79.

Herfindal I, Tremblay JP, Hester AJ, Lande US, Wam HK (2015) Associational relationships at multiple spatial scales affect forest damage by moose. For Ecol Manag 348:97–107. https://doi.org/10.1016/j.foreco.2015.03.045

Hetemäki, L., Seppälä, J. (2022). Planetary Boundaries and the Role of the Forest-Based Sector. In: Hetemäki, L., Kangas, J., Peltola, H. (eds) Forest Bioeconomy and Climate Change. Managing Forest Ecosystems, vol 42. Springer, Cham. https://doi.org/10.1007/978-3-030-99206-4_2

Hlásny T, Krokene P, Liebhold A, Montagné-Huck C, Müller J, Qin H., … Viiri H (2019) Living with bark beetles: impacts, outlook and management options. From science to policy 8. European Forest Institute https://efi.int/sites/default/files/files/publication-bank/2019/efi_fstp_8_2019.pdf. Accessed 25 Sep 2021

Huotari, N. (2012). Huotari, N., Hytönen, J., Tillman-Sutela, E., Issakainen, J. & Kubin, E. (2012) Biomass production of 10 years old downy birch (Betula pubescens Ehrh .) stand in ash-fertilized peatl ... June.

Hytönen, J., Aro, L., Issakainen, J., & Moilanen, M. (2016). Peat ash and biotite in fertilization of Scots pine on an afforested cutaway peatland. Suo, 67(2), 53–66.

Ikonen V-P, Kilpeläinen A, Strandman H, Asikainen A, Venäläinen A, Peltola H (2020) Effects of using certain tree species in forest regeneration on regional wind damage risks in Finnish boreal forests under different CMIP5 projections. Eur J For Res 139:685–707. https://doi.org/10.1007/s10342-020-01276-6

IPCC (2018) Special report on global warming of 1.5°C approved by governments. IPCC, Switzerland

Jandl R (2020) Climate-induced challenges of Norway spruce in northern Austria. Trees For People 1:100008. https://doi.org/10.1016/j.tfp.2020.100008

Kellomki S., Strandman H., and Peltola H. (2019) Effects of even-aged and uneven-aged management on carbon dynamics and timber yield in boreal Norway Spruce stands: A forest ecosystem model approach. International Journal of Forest Research 92:635-647

Kilpeläinen A. and Peltola H. (2022). Carbon Sequestration and Storage in European Forests. In: Hetemäki, L., Kangas, J., Peltola, H. (eds) Forest Bioeconomy and Climate Change. Managing Forest Ecosystems, vol 42. Springer, Cham. https://doi.org/10.1007/978-3-030-99206-4_2

Lauri Hetemäki and Jyrki Kangas. Forest Bioeconomy, Climate Change and Managing the Change; In Forest Bioeconomy and Climate Change, Managing Forest Ecosystems 42, https://doi.org/10.1007/978-3-030-99206-4_3

Lehtonen I, Venäläinen A, Kämäräinen M, Asikainen A, Laitila J, Anttila P, Peltola H (2019) Projected decrease in wintertime bearing capacity on different forest and soil types in Finland under a warm climate. Hydrol Earth Syst Sci 23:1611–1631. https://doi.org/10.5194/hess-23-1611-2019

Mandre, M, Pärn, H., Klõšeiko, J., Ingerslev, M., Stupak, I., Kört, M. & Paasrand, K. (2010) Use of biofuel ashes for fertilization of *Betula pendula* seedlings on nutrient-poor peat soil. Biomass and Bioenergy 34: 1384–1392.

Marini L, Økland B, Jönsson AM, Bentz B, Carroll A, Forster B et al (2017) Climate drivers of bark beetle outbreak dynamics in Norway spruce forests. Ecography 40:1426–1435. https://doi.org/10.1111/ecog.02769

Melin M, Viiri H, Tikkanen O-P, Elfving R, Neuvonen S (2020) From a rare inhabitant into a potential pest – status of the nun moth in Finland based on pheromone trapping. Silva Fenn 54

Miller, K.A., Snyder, S.A., Kilgore, M.A., & Davenport, M.A. (2014). Family Forest Landowners' Interest in Forest Carbon Offset Programs: Focus Group Findings from the Lake States, USA. Environmental Management, 54(6), 1399–1411. https://doi.org/10.1007/s00267-014-0352-5

Minkkinen, K., Byrne, K.A., and Trettin, C. 2008. Climate impacts of peatland forestry. *In* Peatlands and climate change. *Edited by* M. Strack. International Peat Society. pp. 98–122.

Nieminen, M. 2003. Effects of clear-cutting and site preparation on water quality from a drained Scots pine mire in southern Finland. Boreal Environ. Res. 8: 53–59.

Nieminen, M. 2004. Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three Norway spruce forests growing on drained peatlands in southern Finland. Silva Fenn. 38(2): 123–132. doi:10.14214/sf.422.

Nieminen, M., Ahti, E., Koivusalo, H., Mattsson, T., Sarkkola, S., and Lauren, A. 2010. Export of suspended solids and dissolved elements from peatland areas after ditch network maintenance in South-Central Finland. Silva Fenn. 44(1): 39–49. doi:10.14214/sf.161.

Nykänen M-L, Peltola H, Quine CP, Kellomäki S, Broadgate M (1997) Factors affecting snow damage of trees with particular reference to European conditions. Silva Fenn 31(2):193–213

Page, S., Mishra, S., Agus, F., Anshari, G., Dargie, G., Evers, S., Jauhiainen, J., Jaya, A., Jovani-Sancho, A. J., Lauren, A. , Sjögersten, S., Suspense, I.A., Wijedasa, L.S., & Evans, C.D. (2022). Anthropogenic impacts on tropical lowland peatland biogeochemistry. Nature Reviews Earth & Environment, 3(7), 426–443. https://doi.org/10.1038/s43017-022-00289-6

Paivanen, J., and Hanell. B. 2012. Peatland ecology and forestry — A sound approach. University of Helsinki Department of Forest Sciences Publications. Vol. 3. pp. 1–267.

Pekka Leskinen, Giuseppe Cardellini, Sara González-García, Elias Hurmekoski, Roger Sathre, Jyri Seppälä, Carolyn Smyth, Tobias Stern and Pieter Johannes Verkerk. (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

Schelhaas M-J, Nabuurs G-J, Schuck A (2003) Natural disturbances in the European for-ests in the 19th and 20th centuries. Globe Change Biol 9:1620–1633. https://doi.org/10.1046/j.1365-2486.2003.00684.x

Seidl R, Schelhaas M-J, Rammer W, Verkerk PJ (2014) Increasing forest disturbances in Europe and their impact on carbon storage. Nat Clim Chang 4(9):806–810. https://doi.org/10.1038/nclimate2318

Sini Savilaakso, Anna Johansson, Matti Häkkilä, Anne Uusitalo, Terhi Sandgren, Mikko Mönkkönen and Pasi Puttonen (2021) Review: What are the effects of even-aged and uneven-aged forest management on boreal forest biodiversity in Fennoscandia and European Russia? A systematic review. Environmental Evidence Journal 2021.

United Nations (2022) Paris agreement – status of ratification. https://unfccc.int/process/the-paris-agreement/status-of-ratification. Accessed 17 Sept 2022