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Forest carbon payments: A multidisciplinary review of policy options for promoting carbon storage in EU member states

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ABSTRACT

Forest carbon sinks can play an important role in mitigating climate change, but currently only a few policies exist globally where economic incentives are created for forest owners to maintain and strengthen sinks. This article aims to facilitate the design and implementation of governmental payment schemes for forest carbon uptake services by presenting a multidisciplinary analysis of the many challenges involved in such schemes and by proposing potential solutions. We assess the consequences, opportunities, and risks of carbon payment schemes from economic, ecological, social, and legal points of view based on existing literature. Our analysis is set in the context of the European Union (EU), but many of the central findings have relevance for a broader geographical area. The main economic challenges of implementing carbon payment schemes relate to potential leakage, the question of additionality, and uncertain forest-owner behavior. The most important ecological considerations include effects on soil carbon dynamics and biodiversity as well as issues of non-permanence and forest resilience. Our exploration of the social acceptance of carbon payments among the general public, key market actors such as forest owners and forest industry, and other stakeholders suggest that both the process of developing the scheme and its details are significant. Further, our legal analysis indicates that central challenges for carbon payment schemes within the EU rise from the requirement to comply with competition and state aid regulations. Finally, we synthesize our findings and suggest a two-step approach for introducing public carbon payments in an EU member state. Initially, the scheme could be launched *via* De minimis aid or the new aid scheme (GAFSRA). A low carbon price could be applied to moderate market effects, and the payments could be limited to additional carbon storage only. Peatlands, where tradeoffs exist between tree biomass carbon and soil carbon, should initially be excluded from the standard payment scheme, and regulated with command-and-control instruments and measure-based payments instead. In the future, an improved knowledge base and institutional changes may enable schemes that encompass all ecosystem carbon pools on all relevant soil types and create optimal incentives for both forest management and land-use choices by pricing all land-based sinks and emissions. Such schemes could utilize, e.g., cap-and-trade instruments and be complemented by import tariffs to control carbon leakage.

1. Introduction

Forest carbon sinks can play an important role in mitigating climate change, and many governments have included forest-based solutions in their national climate change mitigation plans (Seddon et al., 2020). However, only a few policies that directly address forest carbon sequestration in privately owned forests are in place anywhere in the world. New Zealand has integrated forest carbon storage into its

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national emissions trading scheme (NZ ETS) since 2008, and the state of California has allowed forest carbon offsets in its carbon cap-and-trade scheme since 2013 (Adams and Turner, 2012, Gren and Aklilu. 2016). The small number of currently operating policy schemes, and their absence within the European Union, is largely a result of the multiple complications and challenges involved. Risks of non-permanence of carbon sequestration, additionality issues,[1] leakage, verification issues, and transaction costs, are among the most frequently pointed uncertainties related to forest-based carbon policies (Sedjo and Sohngen, 2012). These uncertainties in mitigation, together with conflicting political interests related to the utilization of forests and the financing of climate efforts, make the creation of effective and legitimate policies challenging. This article presents a multidisciplinary analysis of these challenges and possible solutions.

International carbon accounting systems track changes in forest carbon stocks within the land-use sector (LULUCF), i.e., carbon sequestering biomass growth is counted as removal and carbon stock reducing harvests as emissions. To prevent double-counting, the use of forest-based biomass, for example, in energy production, is exempted from carbon emissions liabilities (Krug, 2018). However, the current policy environment is incoherent. Emissions from large industrial facilities and power plants are regulated by the European Union's Emissions Trading Scheme (EU ETS), but similar incentives to promote the optimal management of forest carbon have not yet been established. As the EU ETS puts a price on fossil carbon, it creates a strong economic incentive to replace fossil inputs with non-fossil ones such as biomass, which are not subject to carbon pricing. This is likely to lead to excessive harvests when forest carbon storage is not regulated. The situation differs considerably from an efficient forest sector climate policy in which both the sequestration that occurs when trees grow and the emissions that occur when trees are used for energy or wood products are priced (Tahvonen, 1995, Lintunen and Uusivuori, 2016, Favero et al., 2020). This incoherence of incentives is likely to be important especially in countries with high share of private forest-ownership.

The carbon neutrality targets of the Paris climate agreement and the European Climate Law (Regulation (EU) 2021/1119) require member states to substantially reduce their net greenhouse gas emissions. Earlier the EU worked towards climate neutrality mainly through creating mechanisms for decreasing emissions in the industrial sector (notably, the EU Emissions Trading Scheme, EU ETS). More recently increasing carbon sinks has also appeared as a policy objective. Regulation (EU) (2018/841) on land use, land-use change, and forestry (LULUCF) requires member states and the EU as a whole to make significant efforts to increase carbon sinks and reduce emissions. The revised LULUCF Regulation (Regulation (EU) 2023/839) defines the rules by which removals and emissions from land use, land-use change, and forest management are accounted towards EU's climate targets for the period from 2021 to 2030, and introduces updates to targets and allocation methods from 2026 onwards. However, the LULUCF Regulation leaves it up to individual member states to develop and apply policies that enable them to reach their designated targets for net sinks. Currently, it seems that most member states and the EU as a whole are likely to fall short of their agreed targets (Hyyrynen et al., 2023) implying that European forest sinks need to be strengthened. The carbon payment schemes discussed in this article provide a policy option to this end.

In this article we evaluate alternative mechanisms that could provide the basis for a carbon payment scheme in which the public sector channels monetary subsidies to forest owners for the provision of carbon uptake services. As our focus is on government policies, market-based voluntary carbon offsetting schemes for forest resources are discussed only briefly. While the basic economic concept of forest carbon payments as a means for internalizing the climate externality theoretically applies to all kinds of forests, the challenges and, hence, possible solutions related to real-life policy implementation are inherently tied to specific bio-geographical and socio-political circumstances. Hence, we focus our analysis on forestry in the European Union. We also note that EU member states are highly heterogeneous in terms of the extent, type and use of forests as well as the importance of the forest sector in the national economy (Forest Europe, 2020).

Using a multidisciplinary approach, we assess the consequences, opportunities, and risks of carbon payment mechanisms from economic, ecological, social, and legal points of view, and present a synthesis of the findings of the different disciplines. As far as we know, our study is the first to explore forest carbon payments from such a multidisciplinary perspective. This allows us to extend our analysis to cover not only the economic incentives created through carbon payments but also the various complications related to ecological, social, and legal conditions that need to be addressed to make forest carbon payment schemes implementable in practice.

The article is organized as follows. First, we describe the theoretical foundations of carbon payments from the government to landowners. Then, in the economic assessment we focus on the structure of the incentives and the economic consequences of their implementation, including the additionality and leakage implications of the payment scheme. The ecological assessment accounts for effects on soil carbon dynamics, biodiversity as well as the issues of non-permanence and resilience related to such payment schemes. In the social evaluation we shed light on the public acceptability of government payments for carbon sequestration. The legal analysis concentrates on the legal limitations on possible carbon payment policies set primarily by the European Union legislative framework. Last, we present the overall conclusions and policy recommendations.

2. Theoretical foundation of forest carbon payments

2.1. Basic properties

The theoretical rationale for carbon payments to forest owners stems from the climate externality generated by forest resource use. Forests generate climate benefits, and forest management affects the size of these benefits. Private decision makers, however, do not fully take these benefits into account, and hence markets fail to internalize their value. From the standpoint of social welfare, neglecting climate benefits distorts the management and the use of forest resources as well as land allocation. This causes a welfare loss. The welfare loss justifies a need for the implementation of public policies to correct the functioning of the markets by pricing the benefits along Pigouvian principles (cf. Pigou, 1920) or by creating market-based solutions along Coasian principles (Coase, 1960).[2] When net carbon fluxes are kept track of following the stock change approach suggested by the IPCC (Aalde et al., 2006), forest carbon pricing can be implemented by subsidizing stock increments and taxing reductions (Lintunen and Uusivuori, 2016).

Forest carbon payments are an example of results-based payments. In contrast to measures-based payments, results-based payment policies allow the targeted economic agents – in this case landowners – to choose what measures to apply to produce the desired results. This flexibility may promote the cost-efficiency of climate change mitigation in the varying economic and ecological circumstances of forestry, and the social acceptability of carbon schemes may also benefit from it. However,

[1] In our terminology, additional carbon sequestration refers to sequestration that exceeds a predefined baseline. This baseline can be based on business-as-usual forest management but, in general, it does not need to.

[2] In this paper, we analyze a policy scheme where the forest carbon externality is priced. We focus on a case where a regulator uses Pigouvian principles to set a price on the externality. However, the price could also be based on market outcomes if forest carbon serves as an offset mechanism or is integrated into a compliance market, such as an emissions trading system. The implications on forest management would be the same as long as the prices are equal.

results-based schemes entail many challenges related to the definition, measurement, and verification of results, and their compatibility with current legal frameworks and other environmental objectives may also be an issue.

A forest carbon payment scheme can be analyzed within the context of comprehensive carbon policies, where a broader group of economic agents, i.e., not only forest owners but also users of fossil and renewable inputs, are either subsidized or taxed for the climate impacts of their actions. For forests, this implies both a subsidy for removals generated by growth and a tax on emissions from harvests (Tahvonen, 1995, Lintunen and Uusivuori, 2016). Additionally, carbon payments can also be extended to owners of wooden structures and buildings. Such payments incentivize increased wood use (i.e., increase demand) and, through their effect on the timber price, they also affect the decisions of the forest owners (i.e., increase supply). Using an alternative approach, focused solely on forest management decisions, downstream market impacts of landowners' timber harvests are integrated into the model by a so-called pickling factor, which rewards the landowner for long-lasting carbon storage in wood products (van Kooten et al., 1995, Assmuth and Tahvonen, 2018).

Forest carbon payments may be organized and financed in several ways. One option – which is the default assumption guiding the legal analysis in this article – is through direct subsidies from the government to forest owners. Another option is the integration of forests into an emissions trading scheme (ETS). The central advantage of integrating carbon payments to a wider market is that uniform carbon pricing across economic sectors promotes cost-efficient mitigation. However, this approach entails significant challenges. A further option is the route of voluntary carbon credits, where companies can claim emission offsetting by purchasing carbon storage credits from forest owners, typically mediated by specialized broker organizations.

Article 6 in the Glasgow Climate Pact (UNFCCC, 2021) strived to establish basic principles for trading carbon offsets internationally, including the distinction between Internationally Transferred Mitigation Outcomes (ITMO), used by buying countries or companies to meet legal compliance criteria and required to demonstrate additionality relative to national emissions reduction targets of the host country of the project, and "mitigation contribution" units geared towards companies taking voluntary actions to support mitigation in the host country. Recently the EU has banned the use of marketing claims such as "climate-neutral" or "climate-positive" based on offsetting activities (European Parliament, 2024). On the other hand, the EU is planning a certification framework for carbon removal activities (Council of the EU, 2024). It remains to be seen whether the marketing claim "mitigation contribution" is seen attractive enough by private firms to galvanize voluntary funding of sequestration activities in forests – probably not in the extent that is required to maintain and strengthen forest sinks in the EU.

To date, New Zealand remains the only country with a semi-comprehensive ETS, in which forestry (but not agriculture) is one of the regulated sectors (Carver et al., 2022). Likewise, in EU member states, the corresponding relevant market would be the EU ETS. In practice, however, linking the forest sector to the EU ETS is beyond the jurisdiction of any individual member state, and would require EU level decision-making and preferably the symmetric inclusion of forestry in all member states. Allowing forest carbon units into the EU ETS market would have to be accompanied by a corresponding tightening of the total emissions cap (e.g., Lintunen et al., 2016). Depending on the cost of increasing carbon storage in forests (discussed in sub-Section 3.1), mitigation through forestry actions might replace some mitigation actions in the energy and industrial sectors. While this replacement could be cost-effective, it might be problematic unless the changes made to the total emission cap could be based on a good baseline estimate for forest carbon sequestration (see sub-Section 3.2).

If the carbon payment scheme is both operated and funded by the government, the price level can be set so that it is deemed suitable for sink targets and fiscal realities. The main issue from the perspective of forest owners contemplating participation is policy uncertainty: will the government maintain the scheme in the future and at what price level? In the case of an ETS, the price of an emissions unit is formed in the market to balance supply and demand, implying some level of volatility. The fact that the emissions trading market is created by policymakers and is potentially subject to significant changes in its rules, makes policy-uncertainty a considerable factor for price formation (c.f. Dai et al., 2022) and the forest owners' willingness to participate.

In the New Zealand ETS, the initial inclusion of offshore Kyoto units and uncertainty regarding future changes to the scheme led to very low prices throughout 2012–2015, with little afforestation and increased deforestation (Evison, 2017, Carver et al., 2022). After 2016, changes to the scheme (e.g., de-linking from the Kyoto market and greater target ambition) have resulted in an increasing emissions price and the considerable increases in afforestation (Carver et al., 2022, MPI, 2023). This suggests that the government's credible commitment to the future of the policy – including the carrying out of design amendments when needed – is vital for decreasing policy uncertainty and, hence, ensuring the forest-owners' willingness to produce carbon removal units.

A central question relating to the pricing of forest carbon storage is how the property rights of the climate benefits are defined. One approach would be to assign the property right of the sinks completely to forest owners, tighten emissions targets in other sectors accordingly, and let forest owners sell offset units to other sectors. Or, equivalently, to pay publicly funded carbon payments for the whole carbon sink. Another approach would perceive carbon sequestration up to a baseline as a common property, in which case forest owners only own the sequestration that exceeds this baseline. An argument in favor of this approach is that current net sinks are a product of historical and current land use and forest management practices that do not entail specific efforts by landowners to increase sinks beyond what is privately profitable. As shown by Coase (1960), the assignment of property rights doesn't change the outcome in terms of efficiency of actions taken, but it greatly influences the distribution of income. Publicly funded forest carbon payment schemes implicitly assume that at least part of the pursued net sink should be assigned as the forest owner's property. We return to this question in sub-Section 3.3.

The distinction between *accounting and reporting rules of national emissions* and *policy principles* can be a source of confusion. We argue that when reporting national emissions, it makes sense to account for all sinks and emissions as comprehensibly as possible. This enables the realistic appraisal of the current situation and, hence, the needs for future policy updates. In theory, policy principles such as the definitions of property rights and responsibilities regarding sinks and emissions can be discussed and agreed upon irrespective of the accounting rules of national emissions reporting, allowing, e.g., the setting of sequestration baselines to control public costs of the carbon policies. In practice, however, accounting conventions tend to shape the ways in which forest carbon policies are carried out and financed, as shown by the unresolved issue of double-counting: Private carbon offsetting projects within EU countries are made near impossible by the fact that any resulting increase in land-use sinks is also included in the reported national land-use sink, which is already subject to the EU LULUCF regulation. This may decrease the obligation to cut net emissions elsewhere in the country and, hence, makes it disputable whether total emissions were actually reduced.

2.2. *Two scheme type options*

Forest carbon payment schemes can be categorized into two main types: one based on carbon fluxes, and one based on carbon stocks in forests. In the former type, the landowner receives payments as the forests grow and sequester carbon but has to pay for releasing the carbon at harvest, i.e., it is based on subsidy-taxation principle on stock changes (Plantinga and Birdsey, 1994, van Kooten et al., 1995). The latter type is based on carbon rent paid to the forest owner depending on the amount of carbon currently held in storage in their forests. The periodic rent describes the (monetary value of the) climate benefit of keeping the carbon stored, or put another way, delaying its release into the atmosphere by one period (Sohngen and Mendelsohn, 2003, Uusivuori and Laturi, 2007). The rental rate is equal to the price of carbon times the difference between the interest rate and the rate of increase of the price of carbon (Sohngen and Mendelsohn, 2003).[3]

Both types of schemes presume that the forest owner owns the sequestered carbon: In the first system the sequestered carbon is purchased from the forest owner (a subsidy) and forest owner needs to buy it back (a tax) in order to harvest and, hence, release the carbon. In the second system, rent is paid to the forest owner. In the payment scheme based on the subsidy-taxation principle, the payments flow in two directions, whereas in the rental scheme the payments only flow in one direction: from the government to the forest owner.

These two ways of organizing the carbon payment scheme have been shown to be equivalent in terms of how they affect the behavior of forest owners under general assumptions (Lintunen et al., 2016). Yet, the two ways differ in terms of the timing of transfers: in a subsidy-tax scheme the greatest subsidy payments are obtained as carbon is accumulated in a relatively young stands (that grow and accumulate carbon at a fast pace) whereas in the rent scheme the greatest subsidies are paid for relatively old stands (which contain a lot of carbon). Hence, the rental approach could be attractive to owners of stands that are good candidates for conservation.[4]

One of the assumptions needed to guarantee the equivalence of the two schemes, is that – in the subsidy-tax system – the initial carbon stock is purchased by the regulator when a forest owner joins in the system (Lintunen et al., 2016). This is a logical requirement given the stated property rights. If the initial purchase is not included in the system, the system will not attract forest owners with mature stands, as they are faced with forthcoming large taxes that are not covered by future post-harvest sequestration subsidies. A flux-based scheme has been used in the New Zealand emissions trading scheme (NZ ETS), called "stock change accounting": forest owners obtain emissions units as their stands sequester carbon, and are obligated to surrender units when they harvest or deforest (Carver et al., 2022).[5] In the NZ ETS, the need for initial purchase is circumvented using a 'surrender cap', which means participants are not liable to surrender more units in relation to any carbon accounting area than the net number of NZUs the forest land has received since being registered in the NZ ETS (Leining, 2022). The issue of initial purchase is also eliminated if the additionality issue is solved using forest carbon baselines that are discussed in sub-Section 3.2. With a baseline, the regulator assumes the property rights of carbon up to the baseline, hence, removing the need for the initial purchase. As a result, forest owners own the rights to additional carbon only.

One possible option would be to run two (or more) scheme types simultaneously, letting forest owners choose which one they prefer. Additionally, the application of a few parallel schemes would allow taking into account the different ecological characteristics and social uses of various forests. For example, the New Zealand ETS includes distinct schemes for plantation-type and semi-permanent forests (Carver et al., 2022). We will return to this option in sub-Sections 4.1 and 4.2.

The equivalence of incentives between the subsidy-taxation approach and the carbon rental approach could also be challenged by the findings of behavioral sciences, as there is evidence that people tend to value losses more strongly than gains of a similar magnitude (Kahneman and Tversky, 1979). For example, taxpayers have been found to be more active in claiming deductions if they have preliminary information on tax deficit (Engström et al., 2015). An administrative advantage of the carbon rental approach is that money flows take place only into one direction as the carbon rents are paid to the landowner by the subsidizing party. This implies that the payment policy could be described and implemented as a form of state aid, instead of a combination of state aid and environmental taxation, which is likely to be more complicated from a legislative point of view. However, the carbon rental approach may lose this advantage if the additionality issue is solved using forest carbon baselines that are discussed in sub-Section 3.3.

3. Economic implications of forest carbon payments

3.1. Implications for forest management and timber supply

In principle, carbon payments increase the incentives of a forest owner to create and maintain carbon stocks in the trees (and, if included in the payment scheme, the soil) of the forest. This may lead to modifications in the ways in which forests are managed, in terms of regeneration efforts, harvesting, and measures to increase timber growth (e.g., fertilization). At the stand level (omitting soil carbon dynamics[6])), carbon payments tend to postpone the final fellings in rotation forestry (van Kooten et al., 1995), postpone and moderate commercial thinnings (Pohjola and Valsta, 2007, Assmuth and Tahvonen, 2018), and possibly increase the planting density (Pihlainen et al., 2014). According to some studies, carbon pricing may lead to a switch from rotation forestry to selective cuttings (i.e., management without clearcuts, also called continuous cover forestry; Assmuth et al., 2018, Parkatti and Tahvonen, 2021). However, Tahvonen et al. (2024) argue that the opposite may be the case if soil carbon is included in the analysis. Carbon pricing may also motivate maintaining commercially less profitable tree species in the stand (Assmuth et al., 2021).

The studies mentioned above assume that baseline forestry entails forest owners maximizing the present value of their net income (i.e., Faustmann-type forest owners). Under this assumption, the effect of carbon pricing on timber supply will be negative in the short run, as the rotation age will be extended, and the thinning intensities reduced. Timber supply impacts will taper off in the long run and might even be positive, if maintaining a higher timber stock will result in higher average annual increments (Lintunen and Uusivuori, 2016). Additionally, carbon payments may have an increasing impact on timber supply through encouraging investments on the growing potential of the forest, such as fertilizing inputs (Uusivuori and Laturi, 2007). Furthermore, a carbon subsidy scheme as such gives the forest owner more incentive to protect the forest against abiotic and biotic risks, such as windthrow, insect damage and disease. Furthermore, the carbon payments create

[3] Given the structure of rental rate, the integration of a rental scheme to an emission trading system requires a mediator that transfers the rentals to the landowners from the allowance auction revenues (cf. Lintunen et al. 2016).

[4] The problem here lies in the near impossibility of distinguishing the forest owners who decide to conserve due to the carbon payment from those who would never harvest anyway, which may be the case if they derive amenity benefits from their forest. This issue is present, if to a lesser extent, in most forest carbon payment approaches, and discussed in more detail in sub-Section 3.2.

[5] After the 2020 scheme amendment, the stock change approach is used only for post-1989 forests registered before 2019 and "permanent" post-1989 forests, see sub-Section 3.2.

[6] The majority of studies on forest carbon payment systems apply the even-aged Faustmann framework with a whole-stand growth model, implying that the rotation age is the sole optimized variable (e.g., van Kooten et al. 1995, Hoen and Solberg, 1997, Akao, 2011, Hoel et al. 2014). Optimized thinnings, i.e., partial harvests, and more complex stand growth descriptions have been incorporated to the even-aged model by, e.g., Pohjola and Valsta (2007) and Pihlainen et al. (2014). Impacts of carbon pricing on forest management decisions in heterogeneous stands – consisting of trees of different ages, sizes and/or species – have been studied by, e.g., Boscolo and Vincent (2003), Goetz et al. (2010), and Assmuth et al. (2021). The aforementioned studies omit carbon storage in the soil.

incentives for afforestation (and avoiding deforestation), resulting in net increases in forested land area (e.g., Sohngen and Mendelsohn, 2003).

As the forest owner balances between carbon income and timber income, the extent to which harvests are postponed or other measures are implemented, and the corresponding effects on supply, depend on the relative prices of carbon and timber. In stand-level studies (e.g., Pihlainen et al., 2014, Goetz et al., 2010), carbon prices in the range of € 20–40 tCO_2^{-1} are sufficient to imply significant changes in management schedules and timber yields. In studies utilizing partial equilibrium forest sector models, the extent to which harvests react to a given level of forest carbon payments varies between the models, which is most likely explained by differences in the modelling of the forest owners' decision making and their flexibility to adjust harvests. The majority of studies apply carbon prices within the range of $ 10–100 tCO_2^{-1} (Honkomp and Schier, 2024). In some studies, even low carbon price levels cause notable supply effects and sizeable increases in carbon sinks. For example, according to Pohjola et al. (2018), a carbon price of € 15 tCO_2^{-1} would lead to a 25 % decrease in harvests in Finland in the short term. On the other hand, some model results (e.g., Sjølie et al., 2013, Guo and Gong, 2017) suggest that carbon prices observed in the EU ETS during 2021–2024, i.e., in the range on € 40–100 tCO_2^{-1}, might not cause extreme shocks in timber markets.

In addition to the size of the impact, the results of forest sector modelling studies differ in terms of the timing of the impact. In line with theory, Pohjola et al. (2018) observe a strong initial impact in the short term, mostly tapering off over the century when the new steady state is approached. On the contrary, according to Sjølie et al. (2013), the impacts on harvests and carbon sequestration strengthen over time, as forest owners have less immediate options to respond to the policy but are able to adapt in ways that take an effect in the long run (notably, changing the method and tree species used for regenerating stands after final harvests).

Price volatility and the expected trends climate policy and climate also affect inferences about optimal forest management.[7] The majority of studies on forest carbon payments have assumed a constant carbon price and a constant growth environment of the forest. However, Ekholm (2016) studies optimal forest carbon storage under increasing carbon prices, showing that the near-term effects on optimal rotation age depend on both initial carbon price and its growth rate. An increasing carbon price tends to make optimal rotations longer if the initial carbon price is already sufficiently high. However, if the initial carbon price is relatively modest, a rapidly increasing carbon price may temporarily shorten the current rotations. Lintunen et al. (2022) also incorporate the effects of a changing climate on stand growth. They show that carbon pricing increases rotations but accounting for changing conditions (e.g., growth, discount rate, carbon price path) have strong impacts on optimal outcomes.

Forests also affect the climate through other channels besides the carbon cycle, for example through albedo, i.e., earth's surface reflectivity, and through emitting volatile organic compounds to the atmosphere (Kulmala et al., 2004, Hallquist et et al., 2009). Lutz and Howarth (2014) argue that incorporating albedo benefits may shorten optimal rotations considerably in areas with snowfall, whereas Matthies and Valsta (2016) found that including albedo along the value of timber and carbon storage did not shorten optimal rotations but increased the optimal share of deciduous species in the tree species mixture.[8] According to Rautiainen et al. (2018) and Lintunen et al. (2022), while carbon storage and albedo exert opposing effects on the optimal timing of harvests, the carbon pricing tends to dominate the joint effects, yet, the total effects vary depending on climatic conditions, the incidence of solar irradiance, and the shadow prices of carbon and albedo.

The costs of forest-based climate change mitigation have been evaluated mostly in projects involving afforestation and reduced deforestation, where the opportunity cost of land-use has a significant role (c.f. Richards and Stokes, 2004, Grafton et al., 2021). The cost of increasing carbon storage through changes in stand management on existing forestland can be defined as the discounted timber income that is lost as a result of these changes (c.f. Pihlainen et al., 2014). Based on stand level optimization studies in the boreal regions of the EU, mitigation through management adaptation seems to be relatively inexpensive compared to other sectors (e.g., Pihlainen et al., 2014, Tahvonen et al., 2024). The strong effects of even low carbon prices on sinks, presented in forest sector modelling studies such as Pohjola et al. (2018), point to the same direction. Hence, excluding forest-based mitigation from the domain of effective economic incentives would imply higher total cost for reaching any emissions reduction target level.

3.2. Issues of additionality, income distribution, and land-use change

Additionality is a pertinent issue when considering carbon payments as a public policy measure. The term refers to whether implementing a policy measure leads into carbon uptake that is additional to the level obtained without it, and if so to what extent. Utilizing non-additional carbon sequestration to offset avoided emissions reductions in other sectors could create "hot air" into the scheme, jeopardizing society's ability to reach mitigation goals in the other sectors and on the whole. Hence, ensuring the additionality of removal units is critical in a setup where those units are traded as offsets in compliance markets. This problem would be alleviated if the level of projected removals were explicitly reduced from the future emission caps to make them tighter (Lintunen et al., 2016).[9] On the other hand, if a carbon payment scheme is funded by the government, it has no direct link to emissions trading schemes regulating other sectors, and if any increases in net sink achieved merely contributes towards an exogenously set net sink target (e.g., the national targets set by the EU LULUCF regulation), imperfect additionality does not endanger mitigation but implies a waste of public funds.

The issue of additionality is tightly linked to the question of distributional justice briefly discussed in Section 2: To whom, and to what extent, should the property right of carbon sinks be assigned? The projected sinks have been included in national plans to reach binding climate goals. As such they are not "hot air", but they have a real impact on emissions from other sectors. The property right questions arise when these plans are enforced through policies. If the forest carbon policy subsidizes the whole carbon sink, it would be a notable transfer to landowners, which the taxpayers could see as a windfall, and, hence, unjust and inefficient use of public funds. On the other hand, from the landowners' point of view restricting subsidies to additional carbon sinks only could be seen as a regulatory taking. To mitigate additionality issues, and to follow the logic of national plans, the whole forest carbon sink could be rewarded with carbon payments paid by the government or the industries through offsets. To mitigate worries related to income transfers, there could be a land tax to compensate the payment income (e.g., Tahvonen and Rautiainen, 2017).

Another question relating to additionality is the difficulty of distinguishing natural vegetation growth from human-induced growth, as only the latter are deemed as additional results of mitigation actions. The issue is complicated by the fact that environmental change has

[7] Recent research suggests that the social cost of carbon, currently and especially in future, is likely to be considerably higher than the currently observed carbon prices (Hänsel et al. 2020, Rennert et al. 2022).

[8] An increased share of deciduous tree species would be beneficial for forest resilience and biodiversity (see sub-Sections 4.2 and 4.3).

[9] The idea is that the other sectors can exceed their emission cap using offsets and this way cover the costs of carbon payments rewarded to the sink owners. The realized level of emissions would be equal to the emission cap plus the magnitude of the sink. Therefore, the emission cap needs to be lower than without the coupling.

contributed significantly to growth enhancement and hence biomass carbon stock accumulation within the last few decades (e.g., Fang et al., 2014, Henttonen et al., 2017). International carbon accounting rules, that have undergone a series of changes after their initial adoption, have made attempts to avoid windfall gains from non-human-induced growth of biomass carbon stocks (see, e.g., Krug, 2018, Böttcher and Reise, 2020, Tsukada and Matsumoto, 2024). The central question is to what level the net removals or emissions of managed forestland, or land that has been afforested or deforested, should be compared to: to year 1990 ("net-net accounting"), to a "reference level" based on simulations, or consideration of removals/emissions without comparison to baseline ("gross-net accounting") (Tsukada and Matsumoto, 2024). The applied accounting approach may have a large impact on a country's apparent climate contribution on the one hand and on the incentives of countries to mobilize its forestry sector for climate mitigation on the other hand (Ellison et al., 2011).

The standard remedy for the additionality challenge in policy design is applying a baseline approach, in which the forest owner is only rewarded for carbon sequestration beyond the level she would provide without the policy measure. Such policy design is equivalent to a policy that combines full carbon sequestration subsidies with a forestland tax (Tahvonen and Rautiainen, 2017), which highlights the distributional and property right perspectives of the additionality question. Based on stand-level analysis, limiting carbon payments to the additional share of carbon leads to the same management changes as when subsidizing all carbon storage, if the baseline is independent of chosen forest management (Lintunen et al., 2016, Tahvonen and Rautiainen, 2017, Juutinen et al., 2018). Baseline levels can be organized in different ways. For example, the landowner may be paid only for carbon uptake which can be shown to exceed the uptake under 'recommended' forest management practices. Alternatively, in the case of even-aged forestry, the baseline level could be set at a certain maturity age, possibly reflecting a privately optimal rotation age of the forest, below which the owner is not rewarded.[10]

These baseline approaches would face the problem of asymmetric information between the landowners and the regulator, as the management preferences of landowners, and hence management without the policy, are not known to the regulator. The problem of asymmetric information could be circumvented by eliminating the subsidies for the baseline carbon storage through site productivity taxation (Tahvonen and Rautiainen, 2017).

Setting up baselines is complicated by the fact that carbon payments have an effect not only on stand-level forest management decisions but also on land-use decisions between forest and other land. Theoretical market-level analysis shows that only paying for additional storage leads to the valuation of forestland below its social value because the landowner receives only a part of the carbon benefits of sequestration. Hence, the landowner has lesser incentives to decrease deforestation and increase afforestation than would be optimal from a social point-of-view. The resulting forest land area, while larger than that without carbon pricing, is smaller than the socially optimal forest land area (Tahvonen and Rautiainen, 2017).[11] The interpretation is the following: Carbon pricing increases the value of forest land and, thus, increases the incentive to afforest (or reforest) and decreases the incentive to deforest. However, these effects will be only partially realized if the carbon storage benefit of forest land relative to other land uses (mainly agriculture) is not correctly priced, which is the case when the subsidies are limited to the carbon storage that is additional to business-as-usual forestry. However, the distortion may not be very significant if there are few plausible alternative uses for the land outside of forestry – which may be the case in some boreal or remote areas.

On the other hand, a subsidy scheme without the additionality requirement is likely to be very expensive for the public sector (Lintunen et al., 2016, Pohjola et al., 2018). Even if a subsidy scheme were funded by emission taxes or allowance auction revenues from other industries, without a baseline the scheme might become too expensive to be accepted by the general public as there are other competing uses for the public funds. One solution for combining correct land-use incentives with fiscal viability would be to subsidize the full extent of carbon storage but eliminate excessive subsidies by general land taxation irrespective of whether the land is used for forestry or agriculture (Tahvonen and Rautiainen, 2017). Another option is to augment additional carbon subsidies with separate land-use change instruments to discourage deforestation (Assmuth et al., 2022) and encourage afforestation.

The New Zealand ETS has dealt with the additionality issue by essentially delimiting carbon payments to newly afforested land, while at the same time including measures to control deforestation in older stands. As New Zealand integrates forestry in its comprehensive (excluding agriculture) emissions trading scheme, some of the costs of increasing carbon storage are transferred to emitting sectors. The NZ ETS differentiates between "pre-1990" and post-1989" forests depending on whether the land was forested before 1990 and remained so until the end of 2007 (excluding indigenous pre-1990 forests) (Leining, 2022). Owners of pre-1990 forests must surrender units if they deforest[12] while owners of post-1989 forests can voluntarily opt in to receive units if they accept certain obligations. For post-1989 forests registered before 2019, "stock change" accounting is applied: owners obtain units for the uptake of carbon as their forest grows but must surrender units if they harvest (i.e., the flow approach discussed in 2.2). Many forest owners have chosen to be credited only up to a "safe carbon" level, i.e., the minimum carbon stock level after final felling assuming replanting, to avoid surrendering units at harvest time (Evison, 2017). After the 2020 amendment, "averaging" accounting is applied to standard[13] post-1989 forests, implying that units are earned only up to the long-term average level of carbon stocks over multiple forest rotations with no need to surrender units when harvesting.

In practice, the NZ ETS forestry scheme has been developed in a direction that rewards afforestation and penalizes deforestation but offers little incentive to increase carbon storage in existing stands. This might be a workable solution for those EU member states in which forests' share of total land area is relatively low and, hence, there is at least theoretical potential for re- or afforestation. On the other hand, such a system is likely to less effective in those (mainly boreal regions) that already have high forest cover and where carbon stocks are more strongly affected by commercial harvests than deforestation.

3.3. Issues of harvest and carbon leakage

Carbon leakage concerns forest carbon payment policies to the extent that such policies decrease local harvests, especially in the short run (e.g., Pohjola et al., 2018). A regional or national carbon policy aiming to increase carbon uptake, may decrease local timber harvests and, therefore, may not be as effective from a global perspective, if the harvests shift to other jurisdictions that do not have similar incentive systems in place. Leakage may occur also within the country applying the

[10] The cost of this kind of baseline would depend on the decisions (e.g., on thinning) of the forest owner. Hence, it would distort the management decisions and thus could be inefficient. The inefficiency could be alleviated with adapting the payments.

[11] Smaller forestland area can also, due to higher timber prices, lead to rotations that are shorter than optimal (Tahvonen and Rautiainen, 2017).

[12] However, most of them received free allocations during the launch of the scheme, resembling what Lintunen et al. (2016) call the "carbon purchase policy".

[13] In addition to the standard post-1989 forests, there is a scheme for "permanent" post-1989 forests with stock change accounting and prohibition of deforestation and clear-fell harvesting for at least 50 years.

carbon payment scheme if participation in the scheme is not comprehensive and forest owners outside the scheme increase their harvests in response to higher timber prices. This applies to all voluntary schemes regardless of whether they are market-based offsetting arrangements or government policies.

However, it is important to distinguish between harvest leakage and carbon leakage, the latter of which (in the context of forestry) has been studied much less than the former. Harvest leakage takes place when decreasing harvests in one country or region increases harvests elsewhere. Carbon leakage takes place when the increased harvests elsewhere have an adverse effect on net carbon sink in the region. The chain of effects is far from straightforward: First, harvest leakage is often mediated through the leakage of forest industrial production to regions with less strict policies, and different regions have varying carbon intensities of production. Additionally, different regions have varying forest growth conditions and management regimes and, finally, varying initial forest age structures. Second, in the long run, increases in timber prices may lead to afforestation or other forest investments in some regions (cf. Favero et al., 2020). These complexities even give rise to the (at least theoretical) possibility of negative leakage (García et al., 2018). Hence, when interpretating the results of studies on leakage associated with the timber markets, it is useful to note the many methodological challenges involved.

In the European context, Kallio and Solberg (2018) and Kallio et al. (2018) project leakage rates as high as 80 % in the event that EU countries constrain harvests to reach LULUCF goals. González-Eguino et al. (2017) argue that under fragmented climate policies (i.e., incomplete participation of countries) terrestrial carbon leakage may be the dominant type of leakage up to 2050. A meta-analysis by Pan et al. (2020) indicates that the leakage rate in the forestry sector is higher than in the sector of energy-intensive industries, approximately 40 % on average. Most studies on carbon leakage focus either on leakage related to the management of deforestation, where agricultural markets are an important driver (c.f. Pan et al., 2020), or on leakage mediated through the timber markets as a result of set-aside (conservation) policies (e.g., Gan and McCarl, 2007). Sun and Sohngen (2009) show that policies that are limited to set-asides and ignore other changes in forest use, such as afforestation, management intensity and rotation length, are more prone to leakage and more expensive. From this perspective, the flexibility of a carbon payment scheme in terms of the actions it covers helps mitigate leakage within the country it operates in. However, this does not prevent leakage abroad if the payment scheme decreases total harvests, which is likely in the short term.

From the point of view of a single EU member state, the requirements of the EU-level regulation are fixed, and each member state seeks to minimize costs when complying with the regulation. In such a setup, states are not required to consider leakage, and the leakage outside EU should be handled at the EU-level, possibly with restrictive import policies. A step towards such import policies is the recent legislation concerning deforestation and forest degradation (Regulation (EU) 2023/1115 of the European Parliament).

3.4. Empirical forest-owner perspectives

Most studies applying an optimization approach to forest carbon storage assume that forest owners are economically rational and, moreover, manage their forest with the aim of maximizing the net present value of harvest revenues and, possibly, amenities. Such assumptions facilitate modelling and predicting the reactions of forest owners to policies that price forest carbon. However, forest owners are heterogeneous in their preferences (Deuffic et al., 2018; Karppinen et al., 2018) and react to policies in different ways (e.g., Baulenas et al., 2021; Juutinen et al., 2021; Kelly et al., 2017). According to a recent large-scale survey, 34 percent of the Finnish forest owners did not assess or monitor the profitability of their forestry in any way (Aalto et al., 2022). The high share of forest owners who do not assess the profitability of their forestry sets a challenge for designing policies based on creating economic incentives for action, as the design is often based on actors' economic rationality and ability to assess the economic benefits of different management strategies. This underlines the importance of providing practical guidance and information as a public policy measure.

According to empirical research, forest-owners' willingness to join a carbon payment scheme may be influenced by, among other things, their economic circumstances (profitability of wood production, size of forest holding, share of forestry in total income) and values and attitudes related to forests and the environment (Håbesland et al., 2016, Karppinen et al., 2018, Sharma and Kreye, 2022). Additionally, risk aversion may play a role in hesitance to join a carbon payment scheme (or to adapt management in any significant way) under uncertainty relating to future prices or circumstances.

Additionally, it is important to note that forest owners operate within an existing framework of taxes and, in some countries, tax deductions and direct forms of state aid. These frameworks, that are often complex, affect the incentives faced by forest owners and may currently distort their decisions in a way that disfavors forest carbon storage (c.f., Koskela and Ollikainen, 2001). Forest carbon payments should be designed taking into account these existing frameworks and minimizing the additional bureaucratic strain on forest owners. In the long-run, regulators should make efforts to reform forest taxation and possible forms of state aid to support (or, at minimum, to not hamper) climate and other environmental goals set for forestry.

4. Ecological considerations of forest carbon payments

4.1. Effects on soil carbon dynamics

Besides tree stand biomass, carbon is also stored in deadwood and soil in forests. The average relative size of the soil carbon pool in forests varies between climatic regions: in boreal forests, the soil carbon pool tends to be significantly larger than the tree biomass carbon pool, while the carbon in temperate forests is more evenly distributed between tree biomass and soil (Dixon et al., 1994, Pan et al., 2011). Aside from the climatic region, absolute and relative sizes of the soil carbon stock depend on soil type. On organic soil such as peat, carbon stocks in the soil per unit area may exceed biomass carbon stocks manifold (Kauppi et al., 1997, Turunen and Valpola, 2020), as peat carbon stocks have accumulated over thousands of years due to the incomplete decay of plant matter in wet, anaerobic conditions. Further, the effects of forest management actions, such as those triggered by carbon payments, on soil carbon dynamics also depend on soil type.

On mineral soil, soil carbon stocks correlate with site productivity, tree biomass stocks and growth, and litter production (Ågren et al., 2008; Lehtonen et al., 2016). Hence, on mineral soil forests management actions promoting higher growing stocks also tend to increase litter input to soil and, hence, soil carbon storage. However, the soil dynamics on peatland differ significantly from those on mineral soil. On peatlands, where the water table is high, tree growth can be enhanced by lowering the water table level by drainage through ditching (Hånell, 1988; Hökkä et al., 2008). Consequently, drainage has enabled and increased timber production and thus profitability of forestry, and peatlands have been extensively drained in many countries. While drainage has enabled increasing tree biomass stocks, it has also exposed the peat layer to aerobic conditions, initiating a strong enhancement in peat decomposition. This often leads to strongly increased release of carbon stored in peat to the atmosphere (Ojanen and Minkkinen, 2019, Uri et al., 2017), which will continue as long as the peat layer remains aerated. The effects of drainage on emissions are further amplified by evapotranspiration of the tree canopy, which increases as the growing stock and leaf biomass in the stand increase (e.g., Leppä et al., 2020a). Hence, on peat soils, management actions that increase the carbon storage of tree biomass typically accelerate the loss of soil carbon.

The fundamental differences in the whole ecosystem carbon balance dynamics of forests on mineral and peat soils should be accounted for when carbon policies are designed. On mineral soil synergies exist between increasing carbon storage in tree biomass and carbon storage in soil, which simplifies their design. On peat soils, the tradeoff, and the opposite responses of carbon storage in biomass and soil renders their design much more difficult. In fact, carbon payment policies developed in economics literature to date – i.e., policies that only consider carbon storage in tree biomass – would likely increase soil emissions to a significant extent if applied on peatlands. This would decrease the total emissions reductions achieved through the policies, in the worst case making the policies harmful for the climate. On the other hand, limiting carbon payment schemes exclusively to forests on mineral soils would imply omitting an emission source of global importance (Leifeld and Menichetti, 2018). As both tree stand biomass and soil are important for the ecosystem carbon balance (Ojanen et al., 2013, Uri et al., 2017), a longer-term goal for policy development should be to design instruments that consider both tree stand biomass and soil carbon dynamics on all relevant soil types.

Using a result-based approach such as forest carbon payments for addressing climate mitigation issues in peatland forests is made difficult by the complexity and the site-specific variability (Ojanen et al., 2013) of greenhouse gas dynamics involved. In the short term, the carbon balance and water quality effects of peatland forests could be significantly improved by specific regulatory measures, such as prohibiting (re)ditching except for stands where the water level cannot be adequately controlled by adapting forest management, e.g., applying selective cuttings (Ekardt et al., 2020). In this context, a parallel, more measure-based payment scheme could be used to support the transition to a selective cutting regime (Leppä et al. 2020b) or to compensate for lost forestry income on parcels where arguments in favor of rewetting are strong (c.f. Kasimir et al., 2018).

4.2. Effects on biodiversity and deadwood carbon storage

The impacts of forest carbon payments on forest biodiversity are mediated by the payment scheme's effects on forest management and hence the characteristics of forests. Currently, the loss of structural diversity of forests, such as the decreased tree species diversity, and low amount of living and decaying large-diameter trees, are key drivers of biodiversity loss in temperate and boreal forests (Siitonen, 2001, Ruokolainen et al., 2018). The main biodiversity challenges of current forest management are related to short rotation periods and low quantities of retention trees, which do not provide a sufficient continuous supply of large living trees and dead wood required by many species (Hagan and Grove, 1999; 2019). In managed boreal forests, typical rotation-based management does not provide sufficient continuity of large dimension dead wood (Peltoniemi et al., 2013), and thus current volumes of dead wood are far below the estimated critical limits (20–30 m^3 ha^{-1}) (Penttilä et al., 2004; Müller and Butler, 2010; Nordén et al., 2018). From the carbon perspective, large dead wood also represents a stock of carbon, which may have much longer decay time than average wood product, and a comparable turnover time to average sawn wood product (Mäkinen et al., 2006, Hurmekoski et al., 2020). Additionally, drainage of peatlands for forestry, as well as clearcuts, cause deterioration of the ecological quality of surrounding waters due to excess loads of nutrients and suspended solids (Stenberg et al., 2015, Nieminen et al., 2017).

A large body of literature suggests that carbon pricing induces longer economically optimal rotations and hence a larger number of large trees in stands, and a larger share of old forest age classes on the landscape level (e.g., van Kooten et al., 1995, Tahvonen and Rautiainen, 2017). Carbon pricing may also favor continuous cover forest forestry relative to rotation forestry (Peura et al., 2018, Assmuth et al., 2018). Additionally, carbon pricing may incentivize forest management that maintains a higher quantity of deadwood, either directly by considering carbon stocks in dead wood in the pricing policies (Pihlainen et al., 2014, Assmuth et al., 2021), or indirectly through increasing the vulnerable period stout wood is exposed to natural disturbances and damage. Furthermore, carbon pricing may motivate retaining a higher number of commercially low-valued deciduous tree species in the stand (Assmuth et al., 2021), which creates biodiversity benefits.

Deforestation is problematic for biodiversity also in regions where deforestation rates are much lower than in the tropics (Powers and Jetz, 2019). As discussed in 3.2, carbon payments may significantly lessen the incentive to deforest, hence helping to protect biodiversity, if negative leakage effects can be avoided. Carbon payments might also increase reforestation and afforestation. In the case of afforestation, the ecological effects depend on the area and habitat that is forested as well as the species composition of the forest (i.e., whether native tree species are used). An example of afforestation causing loss of (other than forest) biodiversity is the drainage of open or sparsely wooded peatlands for forestry, that leads to loss of mire biodiversity by making the ecosystem unsuitable for most mire species due to loss of the wet and open habitat (e.g., Punttila et al., 2016, Fraixedas et al., 2017).

To conclude, it seems that forest carbon payment schemes have significant potential to promote more biodiversity-friendly forest management as a side effect, and to decrease biodiversity loss due to deforestation. It is important to note, however, that longer rotation ages or continuous cover forestry by themselves are not sufficient for guaranteeing biodiversity protection in managed forests, if these forests remain under active management, and only a little dead wood remains at the harvest sites. Hence the implementation of carbon payment schemes should strive to realize the "do no significant harm" principle, promoted, for example, in the EU Taxonomy Regulation (Regulation (EU) 2020/852), by taking into account local biodiversity characteristics and other environmental issues. To his end, dead wood production could be incentivized by accounting for the dead wood carbon pool as a part of the stand carbon stock. Also, using fertilization to increase timber growth and carbon storage affects the diversity of ground vegetation and soil microbiota (Manninen et al., 2009, Huotari et al., 2015). This may lead to further disruptions in the food chains affecting diversity of plant and animal feeding biota (Aronsson and Ekelund, 2004). In contrast, the risk of increased levels of element loads harmful to aquatic biodiversity from drained peatlands after ash fertilization seem to be relatively low (Piirainen et al., 2013, Huotari et al., 2015).

Further, carbon payments schemes should ideally be complemented by regulations and incentive schemes geared specifically towards protecting biodiversity. Interfaces between the terrestrial and aquatic ecosystems are also important in this context. Large buffer zones along streams and other watersheds provide benefits for both terrestrial and aquatic diversity (Koivula and Vanha-Majamaa, 2020; Louhi et al., 2016) as well as water quality by reducing eutrophication and loss of biodiversity. As discussed in sub-Section 2.2, running several carbon payment scheme types parallelly may be possible and even preferable from the perspective of accounting for different forest characteristics and functions. One scheme type could be specifically geared towards forests with high biodiversity values or exceptional ability to provide important ecosystem services (e.g., improvement of water quality), with a design that promotes the production of co-benefits while ensuring that ambitious ecological criteria are met.

4.3. Issues of non-permanence and resilience

A salient issue with mitigating climate change through increasing carbon storage in forests is the non-permanence, i.e., the eventual loss of the achieved carbon stocks. Indeed, the risk of non-permanence may be a key reason why forest-based mitigation remains under-used relative to its cost-efficient potential (c.f. Parisa et al., 2022).

On the level of a forest stand, assuming typical rotation forest management, all (or almost all, if retention or seed trees are left on the site) trees will be harvested and removed from the forest at the end of the rotation. Depending on ecological and economic factors, the final harvest may take place anywhere between 20 to over 120 years after stand establishment, or even earlier in coppice forestry systems. However, as a larger forest estate or a forest landscape consist of a larger number of such stands, each harvested and re-established at different points in time, forest estates and forest landscapes may host relatively permanent average forest carbon stocks. As discussed in the economic analysis, forest carbon payments are designed to motivate forest owners to increase rotation length and adapt thinnings, or change the forest management systems, in ways that increase average carbon stocks over the rotation (and over the forest landscape). The non-permanence means that increases in carbon storage may be reversed either due to management actions (e.g., landowners applying shorter rotations or lower-stocking levels than anticipated, or even deforesting forest plots), or due to natural disturbances.

The non-permanence due to management actions may be at least partially managed through the design of carbon payment policies. As discussed in the economic analysis, the carbon rent approach entails the discontinuation of subsidy payments if the carbon stock is eliminated (Marland et al., 2001, Sohngen and Mendelsohn, 2003, Lintunen et al., 2016). The carbon flow approach to carbon payments may (depending on the chosen reference level) entail an obligation for the forest owner to pay back the subsidies when carbon is released as a result of harvesting. The payback creates a liability, if the forest owner cannot make the payment.

Currently, offsetting schemes typically require that forest carbon projects maintain carbon stocks “permanently” (defined by some arbitrary minimum period, e.g., 100 years) and place a share of potential credits in buffer-pools instead of selling them. From the perspective of economics, such rules are inefficient and fail to recognize that as immediate reductions in net emissions are (at least somewhat) more valuable than similar net reductions realized in the future, short-term carbon storage indeed has value (Parisa et al., 2022). An alternative consistent with economics and the logic of emissions trading is deriving a mathematical formula to define the number (in tons) of carbon held for a certain period of time that has equal value to a 1-ton immediate release of CO_2 (Parisa et al., 2022, see also van Kooten, 2009 and Groom and Venmans, 2023). Such explicit comparability is obviously highly useful for approaches where forest units are traded on a compliance market. For an EU member state aiming to increase its carbon sinks to comply with exogeneous sink targets, the quantification of permanence may have a different role: it may help to forecast the potential for and challenges in not only increasing sinks in the short term but also maintaining them in the future.

Peatland forests represent a special case of non-permanence issues as measures used to increase carbon storage in trees are highly likely to hasten the loss of the carbon stock in the peat soil (Ojanen and Minkkinen, 2019, Ojanen et al., 2019). This implies that carbon storage in the peat soil – which if left undisturbed, would be quite permanent or even increase (e.g., Roulet et al., 2007, Turunen et al., 2002) – is replaced by carbon storage in trees, which is subject to many sources of non-permanence.

Increased risks to permanence of carbon stocks brought about by climate change include drought, extreme weather events, fires, as well as plant diseases and the spread diseases and pests to new areas (Seidl et al., 2014, 2017). These risks require attention from carbon policies. Many of the same factors that increase carbon stocks in forests, also increase the exposure of the forests to possibly catastrophic disturbances with subsequent losses of forest carbon stocks. Typically, larger and taller trees, especially near steep stand edges, expose forests to wind disturbances (Suvanto et al., 2019) and bark beetles (Kamińska et al., 2021), while increases in stand biomass imply also increased fire load in forests, and depending on the situation also suggest increased exposure to fires (cf. Daigneault et al., 2010). Peatland forests again, are a special case for forest fires, as peat fires may in the worst case lead to massive losses of long-term carbon storage (Page et al., 2002). Peatland fires may continue by smoldering for a long time (Rein and Huang, 2021) and they are difficult to extinguish.

The permanence of increased carbon storage in forests, and indeed the maintenance of current carbon storage levels, are also dependent on the health of forest ecosystems, i.e., the general condition and disease/pest status of forests, which affects their ability to resist and recover from more serious damage. However, forest resilience is under significant pressure due to biodiversity loss and the increased transmission of forest diseases and pests, and climate change, particularly climatic drying in many regions (Trumbore et al., 2015, Gauthier et al., 2015). Forest resilience can also be impaired by chronic root-pathogens, which decrease the carbon sink capacity of stands, and expose them to secondary disturbances such as windthrow and bark beetles.

Evidence exists on the resilience benefits of mixed-species management (e.g., Jactel et al., 2017). Increasing tree species diversity e.g., avoids serious whole-stand damage by specialist pest/pathogens, constrains pest/pathogen population size and growth rates due smaller and sparser resource pool, and increases the probability of successful (natural) recovery of biomass. Additionally, continuous cover management may hold some resilience benefits over rotation forestry. There is some evidence that uneven-aged and more complex forest structures are less exposed to wind damage except when winds get extreme (Everham and Brokaw, 1996; Díaz-Yánez et al., 2017), while steep forest edges typical to even-aged stands are known to be vulnerable to winds (Dupont and Brunet, 2008, Suvanto et al., 2019). On the other hand, there are also suspicions that frequent harvesting visits in continuous cover forests (selection harvesting) may induce physical damage to remaining trees and their root systems, with increases the probability of pathogen invasions. Longer rotations and fresher deadwood may promote the spread of some pests, while more decayed dead wood is rather considered to promote species that are antagonist to some important forest pests (Johansson et al., 2007).

It is important to note that natural disturbance risks and factors influencing forest health vary greatly by local conditions. A few guiding principles can be presented, though. To reduce the risks of natural disturbances on forest carbon stocks, payments should favour management systems where diversity of forests is increased at all levels, instead of favouring homogeneous single species forests (particularly, in Europe, on the cost of Norway spruce monocultures, Dobor et al., 2020; Kamińska et al., 2021). Policies should also account for the adaptation to climate by targeting increased resilience of forests (Galik and Jackson, 2009), e.g., by favouring climate-resilient (e.g., drought resistant) tree species. For forested peatlands, particularly in the regions where climate is drying, policies should aim at minimizing the negative impacts of drainage through ditching (typical in peatland forestry), as it increases soil carbon emissions (Ojanen and Minkkinen, 2019) and exposes the peatlands to fire (Turetsky et al., 2011).

5. Social acceptance of forest carbon payments

5.1. Different levels of acceptance

Any policy measure aimed at changing behavior typically creates group-wise effects as experienced by different groups of actors. Here, Wüstenhagen et al. (2007) provide a useful guiding frame to examine the types of social acceptance relevant to forest carbon payments: socio-political, market, and community acceptance. They enable a balanced analysis of the potential social effects with emphasis on multilevel nature of policy implications and a wealth of different kinds of stakeholders. Each of the three are explored in the context of carbon payments below.

5.2. Socio-political acceptance

The first of the three, socio-political acceptance, refers to general public acceptance and the political atmosphere in society related to the proposed policy measure. In this context, carbon payments are intrinsically linked with striking a balance between the benefits of addressing climate change, and the potential costs and other negative effects. The general public's attitudes towards climate change and climate actions are thus one factor in determining the socio-political acceptability of carbon payments. As the public's awareness and concern of climate change and climate anxiety especially among the youth are high (EC 2021; Hickman et al., 2021), it can be assumed that the public in many countries expects effective climate action and would find it legitimate to allocate public funding to carbon payments – particularly as the policy would not require most citizens to take any action or to change their behavior.

However, there are likely to be differences among countries depending on the role of forestry. In Finland, for example, the acceptability of forestry measures and policies have traditionally been framed through a lens of profitability of the forest industry and its link to domestic welfare (Kotilainen and Rytteri, 2011). Thus, if forest industry actors are successful in framing a proposal for a carbon payment scheme as a threat to the wider forest sector – and indirectly, national economy – it would increase the likelihood of being opposed by the general public and thus political decision-makers. Although environmental, sustainability, and climate perspectives on forestry have become more prominent and more influential in shifting the framing (Kröger and Raitio, 2017), the different framings on EU's forest related policies demonstrates how the relations between different actors with different interests – profits, climate, biodiversity, wood production – are ridden with tension (Elomina and Pülzl, 2021). These tensions further influence the public perceptions.

5.3. Market acceptance

Socio-political acceptability is intrinsically linked with market acceptability. While the emphasis of market acceptability is on how the costs and benefits of a policy measure are distributed, the key market actors wield significant power in framing both market and socio-political acceptability, as their views and actions affect not only other market actors but political actors, too. For example, representatives of the forest industry are likely to perceive that a national carbon payment scheme would compete with their interest by decreasing the supply of timber in the short term, hence increasing costs (cf. Pohjola et al., 2018). Consequently, the forest industry in Finland has been reluctant in its approach towards different carbon sequestration incentives and measures (Metsäteollisuus, 2020).

Setting up a publicly funded carbon payment scheme potentially conflicts with the interests of actors that currently offer (or would wish to offer) private carbon offsetting services. The first point of conflict is obvious: the public scheme and the private offset providers compete for the same mitigation units provided by forest owners. However, the actual target of (potential) opposition of these interest groups might not be the publicly funded carbon payment scheme itself, but rather the EU's policy emphasis on country-level sink designations, with its implications on the still unresolved double-counting issue (see sub-Section 2.1), than on the promotion of a functioning private carbon market. More generally, the willingness of private sector actors and lobby groups to accept carbon payments depends on the specific characteristics of the policy measure. Some of these factors are linked to path dependencies, related for example to large infrastructure investments, which deter some businesses from supporting climate action (Wüstenhagen et al., 2007).

The key actors regarding market acceptance of carbon payments are forest owners. For forest owners, the acceptance of the policy will depend on the manner of implementation of the measure and the forest management preferences of the individual forest owners. It can be assumed that as a voluntary economic incentive, carbon payments will not face significant resistance among forest owners. However, the forest owners' willingness to participate in carbon schemes has varied in earlier studies from low interest (Markowski-Lindsay et al., 2011) to somewhat higher figures (Thompson and Hansen, 2012). Generally, financial incentives for carbon sequestration have been found to increase forest owners' interest to participate in such activities as opposed to regulative and restrictive measures (Karppinen et al., 2018).

According to the literature review by Karppinen et al. (2018), preservation of ownership rights and the forest owner's own initiative were (in addition to monetary incentives) important elements of policy instruments related to forest owners' willingness to participate in programs promoting carbon storage. The interest of forest owners was reduced by the long duration of the contract, difficult contract conditions and by a possible penalty for terminating the contract in the middle of the contract period. Furthermore, the willingness may be dependent on how carbon compensation is implemented in practice. A recent study in Finland (Koskela et al., 2021) found that if incentivized with public money, 56 % of forest owners were willing to delay final felling, 41 % would be willing to use fertilizers to improve timber growth, and 35 % would delay selective harvests. Furthermore, 16 % of forest owners were willing to leave their forests as carbon storage and cease harvests entirely.

However, forest owners are not a homogenous group, and their interest to participate in carbon payment schemes varies. For example, many landowners would require substantial monetary incentives to participate in a carbon scheme, but some would be willing to participate for a low payment or even without payment (Khanal et al., 2017). A commonly used method to analyze forest owners' heterogeneity is based on their objectives (Ficko et al., 2019, Kuuluvainen et al., 1996). In Finland forest owners have been categorized into five groups based on the objectives of their forest ownership: those with multiple objectives; recreational users; owners looking for secure and steady income; self-employed owners; and indifferent forest owners with no clear pattern of objectives (Karppinen, 1998; Hujala et al., 2013; Karppinen et al., 2020). Forest owners whose primary objectives relate to timber production and income may have a higher threshold to participate in carbon schemes, whereas those with multiple objectives and emphasis on recreational use (Khanal et al., 2017) or non-market forest amenities (Håbesland et al., 2016) may be more open for such a scheme. Also, forest owners' views on climate change impact their willingness to participate in the carbon schemes (Håbesland et al., 2016). As the forest owners' heterogeneity has significant impacts on their willingness to participate and requirements for carbon payment level, the monetary incentives should be supplemented with education and guidance programs that take the forest owners' different motives into account (Khanal et al., 2017, Wade and Moseley, 2011).

Additionally, it is important to note that the views of forest owners are not fixed. Acceptability is dependent on temporal and spatial contexts and will reflect the changes in trends and in the public mood more broadly in society, thus enabling a wealth of actors to be able to influence acceptability (e.g., Peltomaa et al., 2016).

5.4. Community acceptance

Community acceptability is not independent from socio-political or market acceptability, but it can be approached rather differently than the other two. Whereas socio-political and market acceptability focus on a higher level and wider groups of actors, community acceptability places emphasis on individual actors and their agency to choose their actions. Hence, the community acceptability of carbon payments should not present a major barrier to the policy measure, as the question whether to participate or not would be placed on each individual forest owner.

From forestry professionals' perspective, there may be a concern that an increase in carbon sequestration could reduce the demand for their expertise and services (currently mainly the planning of harvesting and regeneration operations) and this can spark resistance against the policy. Increasing carbon sequestration requires changing forest management practices (e.g., adaptation of thinnings, longer rotations), leading to stands which to some forestry professionals might look poorly managed. Such 'poor' management of forests can even be against the professional ethics, as has been discovered in the context of agriculture with farmers and environmental subsidies (Huttunen and Peltomaa, 2016). On the other hand, carbon sequestration may lead to increased demand for different kinds of advisory services and with time, create new forestry management culture. Increase in carbon sequestration due to carbon payments may also over time affect the local community's understanding of recreationally valuable forest. Thus, when assessing community acceptability, the ever-changing spatial and temporal contexts in society hold true here, too (Wüstenhagen 2007). A key factor then is whether the members of the local community trust those in power to promote the community's interests.

Finally, even if the different actors would view carbon payments positively, this does not directly imply that they are going to actively join a carbon scheme. Forest owners' willingness to enter into carbon payment contracts will depend on how they are defined, what specific implementation measures they require, and how the compensation itself is organized. Thus, there are two interlinked aspects to be considered: the policy and its substance, and the process of developing and finalizing it (Busse and Siebert, 2018). It is possible to influence the perceived acceptability of the policy during the design and implementation process.

6. Legal interpretations of forest carbon payments

6.1. Background and definition of state aid

This section deals with the legal uncertainties and limitations related to a carbon compensation scheme within an EU member state. Key questions relate to the implementation and the legal basis of the scheme. In the following, we discuss different options for the carbon payment scheme, while excluding certain alternatives (Table 1). As payments for carbon storage are granted from public funds, the aid must be compatible with state aid rules. For EU member states, the rules on granting state aid to economic operators, such as forest owners, are set out in the EU's state aid regulations. Under a carbon payment scheme, the state pays forest owners a subsidy in order to provide a financial incentive for them to increase the carbon stocks in their forests. It is a transfer of public funds to economic operators and therefore the admissibility of such a scheme is subject to EU state aid rules.

Any measure taken by a public authority to improve the economic conditions of certain undertakings in a way that may distort competition constitutes state aid. The scope of state aid regulation is wide and includes direct aid and, for example, tax advantages or different forms of financing granted below market prices or conditions. The Treaty on the Functioning of the European Union (TFEU) governs the European Union's competition policy including the use of State aid in the member states. An advantage is classified as state aid if it is (Art. 107): 1) granted by a member state or through State resources; 2) selective, i.e., favoring certain undertakings or the production of certain goods; 3) distorts or threatens to distort competition; and 4) affects trade between member states. As a starting point Article 107 TFEU determines that state aid is prohibited. However, there are many exceptions to this rule, and different kinds of aid may be permitted in certain circumstances (Blauberger, 2009, Ferre, 2021).

The competence to decide the compatibility of a proposed aid scheme with the common market lies with the European Commission. There is a general requirement to notify and seek Commission's pre-approval for new aid schemes. However, certain aids are excluded from this pre-approval obligation. These include situations where either Commission Regulation (2023/2831) on de minimis aid (later referred as "De minimis Regulation") or the so-called agriculture and forestry block exemption regulation, Commission Regulation (2022/2472) (later referred as "AFBER") applies.

Table 1
Alternatives of Implementing a carbon payment scheme under EU legislation.

Alternatives	Pros	Cons
The AFBER	• No pre-notification requirements	• Does not allow results-based aid scheme • Covers only loss of income or additional costs up to 200€ per hectare
Market-based implementation	• Not considered as state aid • Has future potential if carbon sink markets develop	• No existing carbon sink markets in the EU yet • Difficult to determine the market price • Difficult to determine whether the payment is in fact market-conform
De minimis aid	• No pre-notification requirements • Applicable to any kind of aid	• Max. compensation 300 000 € / 3 years / economic operator • Requires record keeping and monitoring due to the limit
New aid scheme (GAFSRA)	• No monetary limits • Can be applicable to forest-based greenhouse gas removal • Allows results-based scheme or incentive payment up to 20 %	• Pre-notification required • Commission's approval uncertain • Administration costs • Incentive effect required

6.2. Inapplicable options: agriculture and forestry block exemption regulation and market-based implementation

The aids listed in the AFBER have been declared compatible with the internal market by the European Commission under Art. 107(2) and (3) TFEU and can be implemented immediately without notification. Under Art. 36 aids aiming for forest-environmental-climate services and forest conservation are accepted with some limitations and removing them from pre-notification requirement. The maximum aid intensity is 100 % of the eligible costs and shall not exceed 200 € per hectare per year. Here the aid is subject to the actual costs of the forest owner, i.e., loss of income or additional costs, but does not allow aid that exceeds these or is determined on the basis of carbon sequestered.

Another relevant question related hereto is whether a carbon payment scheme could be implemented outside of state aid rules, i.e., by market-based means? According to the market economy operator principle (see Robins and Puglisi, 2021), an advantage received by a company does not constitute state aid if the "advantage" is market-priced and has or could have been obtained under normal market conditions (Raitanen et al., 2013).

A market-based model, however, is problematic, as there is yet no existing carbon sink market in the EU from where the prices of the carbon sequestered could be derived. On the other hand, there is a market for industrial emissions (the EU ETS), and in principle this could be used to derive the price for sinks (essentially negative emissions). Furthermore, international voluntary carbon offset markets are currently taking form rapidly (Institute of International Finance, 2021). While voluntary carbon offsetting entails many unresolved issues – notably, those of additionality and lack of common standards – it is likely that some sort of price level for carbon sinks will emerge in the near future (High-level commission on carbon pricing and competitiveness, 2019). Yet in this current situation, it is probably impossible to determine the market price and whether the value and other terms of the advantage are in fact market-conform, i.e., in accordance with the market economy operator principle.

6.3. Potentially applicable options: de minimis aid and a new aid scheme

State aid meeting the criteria in Article 107(1) of the TFEU constitutes state aid and requires notification to the Commission. However, under Article 109 of the TFEU, certain categories of aid can be exempted from this notification requirement. One of such categories is De minimis aid. On that basis and in accordance with the De minimis Regulation (2023/2831), aid granted to a single undertaking over a given period of time that does not exceed a certain fixed amount, is deemed not to meet the criteria laid down in Article 107(1) of the TFEU and is therefore not subject to the notification procedure. The maximum amount of de minimis aid per individual beneficiary is 300 000 € per 3 years (Art. 3(2) of De minimis Regulation 2023/2831). However, the authorities granting de minimis aid are required to make decisions and keep records on any de minimis aid granted so that the potential over-cumulation can be monitored (Art. 5 and 6 of De minimis Regulation). The downside of developing carbon payments on the basis of De minimis rules is that there is a maximum of 300 000 € compensation per forest owner per three years resulting in need for potential payment cuts to certain major forest owners. Similarly, the maximum amount can lead to carbon payment cuts in case certain forest owners receive other de minimis aid for their business activities as these aids will be cumulated.

Another possibility for the establishment of carbon payment scheme would be to seek for Commission's approval to a new aid scheme based on the recently adopted Guidelines for State aid in the agricultural and forestry sectors and in rural areas 2022/C 485/01 (GAFSRA) (European Commission 2022). The new carbon payment scheme could be based on Part II section 2.3 of the guidelines concerning aid for forest-environment and climate services and forest conservation. According to the guidelines, the arrangement receiving aid should generally last for 5–7 years, which is in line with the proposed carbon compensation model.

The maximum amount of aid is determined either based on the value of the climate service produced (Section 557b of the Guidelines) or on the combined value of income loss, additional costs, partial transaction costs, and incentive payments (Section 557a of the GAFSRA). Firstly, according to section 557(a) of the guidelines, this type of state aid can be a compensation to beneficiaries for all or part of the additional costs and income foregone resulting from the commitments made. It may also include transaction costs and an incentive payment up to 20 %.

According to the new guidelines section 557(b), collective schemes and results-based payments schemes such as carbon farming systems are also allowed. This means that the carbon compensation scheme does not necessarily have to be based on compensation for eligible costs, which would be directly derived from additional costs or income foregone, but instead, the aid could be subject to the achieved result. The results-based approach in section 557(b) applies to environmental and climate services in the forestry sector, for which compensation is not available from the market. In this case, results-based aid can be paid based on the value of environmental and climate services, and aid can be granted up to the value of these services. It appears that both the increase in carbon stocks and carbon sinks are types of forestry sector environmental and climate services, which do not receive compensation from the market.

New aid scheme shall be notified to the Commission and if accepted, the EU State Aid rules require that the aid granted on the basis of the scheme is applied for in advance and that the expenses are reported afterwards. In addition, the aid must have an incentive effect meaning that the aid needs to conform to additionality, i.e., it must show results beyond what would have taken place without the aid (GAFSRA). These aforementioned requirements however do not relate to de minimis aid. Thus, it is submitted that setting up a new aid scheme can be a more bureaucratic, uncertain, and burdensome process than setting up a carbon payment scheme on the basis of the de minimis regulation.

7. Synthesis and policy recommendations

Climate change and biodiversity loss pose fundamental threats to the environment and humanity. On a global scale, forests play a key role in addressing both of these threats. In this article we have discussed carbon payments as a means to enhance forests' capacity to serve as carbon sinks in combating climate change. Actually implementing a carbon payment scheme would be a convoluted challenge with a multitude of economic, social, ecological, and jurisdictional ramifications. In this article we have explored such a scheme in a multidisciplinary context. Based on our review, we have outlined two alternative suggestions for the implementation of the scheme. The suggestions are discussed below and summarized in Table 2. Our suggestions regarding the near-term implementation take into account current institutional limitations and gaps in the knowledge base. The long-term solution outlines the features that the scheme should aim to have over a longer planning horizon.

In the context of economic theory, payments to forest owners for enhancing or maintaining carbon sinks is a fairly straightforward example of Payments for Ecosystem Services (PES). Markets fail to value the climate externality generated by forests, which then gives the justification for public policies to interfere.

If the carbon payment scheme is funded by the government, the system should use the scarce public funds efficiently to gain the acceptance of taxpayers and policymakers. Hence, it would be preferable to restrict the payments to additional carbon sequestration only, i.e., sequestration that exceeds a predefined baseline. In this case, the choice of baseline affects the distribution of income between taxpayers and forest owners. If the system is linked to an existing ETS and the cap of the ETS cannot be adjusted credibly, the baseline should be based on the level of sequestration that the forest owner would provide without carbon payments. Ensuring this type of additionality is more challenging in existing forests than in the case of afforestation, due to the difficulty of

Table 2
Challenges and solutions for implementation of forest carbon payments.

Identified challenges and bottlenecks (Political institutions / Knowledge base)	Proposed solution for near-term implementation	Future solution assuming favorable development in institutions and knowledge base
Excessive government expenditure on payments (P)	Payments for additional carbon storage only, complemented with separate land-use change instruments if needed	Pricing all additional land-based carbon fluxes (agriculture, forestry, and other land uses)
Market disruption and carbon leakage (P, K)	Launching with low, gradually increasing carbon prices	As worldwide carbon pricing is unlikely, carbon tariffs for imports may be applied
On peatlands: complex soil carbon dynamics, tradeoff between carbon storage in trees and soil (K)	Limiting the standard payment scheme initially to forests on mineral soil, with ditching regulation and measure-based payments on peat soil; research efforts targeting peat soil	Extending the carbon payments to all ecosystem carbon stocks on relevant soils
Need to observe 'do no significant harm' principle for other environmental targets (P, K)	Including minimum levels for other environmental targets in scheme conditions	Utilizing synergies between environmental targets, minimum levels where needed; policies for other environmental targets
Risk of reversal due to (catastrophic?) forest disturbances (K)	Carbon rent type of scheme alleviates liabilities; considering non-permanence when quantifying mitigation potential of forests	Scheme design to promote efficient and acceptable risk-sharing between parties; adapted and resilient forest management
Socio-political acceptance and forest owners' willingness to participate (P)	Launching with low, gradually increasing carbon pricing to moderate market effects; voluntary participation and option to choose preferred scheme type; guidance	Deliberative design of scheme to enable balancing different interests; elimination of conflicting incentives
Legal restrictions on state aid within the EU (P)	De minimis implementation or the new aid scheme (GAFSRA).	Market-based, e.g., cap-and-trade, implementation.

defining baseline forest management.

For near-term implementation, we suggest defining baseline management according to current forest management recommendations, or more simply, using sequestration averages based on site productivity. As the application of the additionality principle could lead to less-than-optimal incentives for avoiding deforestation and increasing afforestation, the scheme could be complemented with specific land-use change instruments (deforestation fee, afforestation subsidy) in those EU member states where land-use change is significant. The long-term solution should include pricing all land-based sinks and emissions, including those from agricultural and urban land, which would then provide correct climate incentives for both forest management and land-use allocation. This is in line with the EU's plans to develop carbon pricing for the agricultural sector (Bognar et al., 2023).

In the long run, at least in principle, carbon payments can simultaneously increase forest carbon stocks and timber supply. The prospects of this win-win case should be studied further, as it is likely to play a large role in the socio-political acceptability of carbon payment schemes, especially in countries with large and influential forest industries. Moreover, the risk of harvest leakage due to payment schemes is significantly influenced by the schemes' short- and long-term effects on timber supply.[14] To soften the effects of market disruption and harvest leakage, we suggest that a carbon payment policy is introduced with low or moderate carbon prices which could then be increased over time. In an ideal first-best world, forest carbon payments (or other policy instruments that internalize the climate externalities of forests) would be applied worldwide to prevent leakage. A following increase in the world market prices of timber would then enable forest industries to shift part of the increased price burden to consumers. However, given that most individual countries are unlikely to be willing to accept a single global policy, the leakage problem could be managed (at least to some extent) through EU-level carbon border adjustment mechanisms or other import tariffs on imported timber and forest products, as exemplified by Regulation (EU) 2023/1115 of the European Parliament. Further research is needed on their multilateral implementation utilizing models that have a sufficiently detailed description of forest resources and forest-owner decision making.

The fundamental differences in the carbon dynamics of forests on mineral and peat soils should be accounted for when carbon policies are designed. On mineral soil, there are synergies between increasing carbon storage in trees and in soil, which simplifies policy design. On peat soils the opposite responses of carbon storage in trees and soil create a trade-off, which makes policy design more difficult. As a practical recommendation we suggest initially limiting the standard carbon payment scheme to contexts where there are no tradeoffs between tree biomass and soil carbon storage, namely mineral soils, so that the payments could be based on the carbon content in the tree biomass only. To address emissions from peatlands in the short term, we recommend regulation of ditching combined with a parallel measure-based payment scheme to support alternatives to drainage. As peat soils globally hold massive carbon stocks that may be substantially depleted by drainage and subsequent fire, efforts should be made to improve the understanding of the complex water and carbon dynamics of peatlands. This would ideally enable designing policies that extend incentives to the total ecosystem carbon stock, the soil component of which could be determined through a cost-effective combination of measurements and modelling.

In addition to helping mitigate climate change, behavior incentivized by forest carbon payment schemes may contribute positively or negatively towards other environmental goals. These side effects may be decisive for whether a payment scheme is deemed acceptable by local communities and the wider public. Potential synergies or tradeoffs relative to other goals are also relevant to decision makers who may wish to maximize the social benefits (and the likelihood of complying with international commitments) given a limited budget. Biodiversity loss in terrestrial and aquatic ecosystems is a high-priority environmental issue directly linked to forest management and land-use changes.

In rotation forestry, carbon payments tend to lead to more mature forests. Furthermore, carbon payments may favor increased deadwood quantities in forests, especially if deadwood is included in the regulated carbon stock. Carbon payments may also discourage deforestation as they improve the relative economic value of forests compared to other land uses. Hence, besides increasing the carbon sinks, carbon payments have the potential to combat biodiversity loss. However, the realization of this potential synergy is not automatic but depends on the design of the scheme and the eventual choices of landowners – which may be hard to predict. This implies that in order to follow the 'do no significant harm' principle, specific safeguarding conditions regarding the protection of, e.g., habitats and water quality, may need to be included in forest carbon payment schemes, which is our suggestion for initial implementation. In the long run, a mix of policy instruments could be designed to address multiple environmental objectives at minimal cost.

Carbon sequestration into forest biomass is not permanent. Harvests and natural disturbances rerelease it into the atmosphere. In a subsidy-tax type of payment scheme a subsidy is paid as if sequestration was permanent, and when carbon is released, a corresponding reimbursement creates correct incentives. Yet, the reimbursement creates a liability. If the forest owner can or will not reimburse the carbon subsidies, this will distort the incentives (and undermine the quality of the carbon offset, if forests are a part of such mechanism). In a carbon rent type of scheme, the carbon payments are based on the value of postponing the release of carbon and they can be adjusted for the risk of natural disturbances. Therefore, carbon rent schemes do not include reimbursements. Although the net present value of cash flows in both types of schemes can be made equivalent, the need for reimbursements can make the subsidy-and-tax scheme look more punitive and, therefore, less attractive to forest owners than carbon rent.

Increased risks to the permanence of storage caused by climate change include increased drought, extreme weather events, fires, as well as plant diseases. Diseases and pests may also spread to new areas. These risks call for adaptive and resilient forest management and need to be taken into account when designing forest carbon policies. Ideally, a carbon payment scheme should be designed to maintain or increase the incentives of forest owners to engage in risk-reducing activities, while at the same time distributing risk between the society and the forest owner in a manner that promotes the social acceptability of the scheme. When it comes to relatively small-scale forest disturbances, it is likely that private forest insurance contracts may be extended to include the associated loss of carbon revenues. However, private insurance may be unequipped to deal with large-scale catastrophic events such as forest fires spanning large geographical regions, and the government may need to take a role in attenuating private losses. Moreover, risks to permanence should be taken into account when evaluating the realistic climate change mitigation potential of forest carbon payment schemes.

The increased public discussion on forests' potential to mitigate climate change might improve the general acceptance of using carbon payments to enhance carbon sequestration in forests. It can be further assumed that forest owners' attitudes toward a carbon payment scheme are positive rather than negative, as a such scheme would introduce an additional or alternative (relative to timber harvesting) income source to forest owners. However, forest owners are a heterogenous group, and individual owners differ from each other in terms of their willingness to participate in carbon payment schemes and the payment level they require. Hence, the monetary incentives should be supplemented with education and assistance programs that take the forest owners' different motives into account. Furthermore, practical guidance is needed to make the logic of payments and the required forest management actions

[14] However, carbon leakage following forest carbon payments should not be a problem at the EU level leakage due to a binding target for total LULUCF net sinks.

understandable for forest owners. At the same time, improving the understanding of forest owners' attitudes and behavior would be highly useful for designing cost-effective payment schemes and for evaluating their likely effects on carbon storage and the provision of other ecosystem services, including the production of merchantable timber. As these other forest ecosystem services might also be subsidized, the interaction and coherence of the subsidy systems targeting separate ecosystem services should be studied.

Key actors in forest-owner education and outreach are found at forestry expert organizations. To ensure the successful implementation of carbon payments, it is crucial to bring the experts working in these public and private organizations onboard and guarantee that they can see their role in the implementation. Increasing awareness of potential advisory services among these groups would likely benefit the successful implementation of payment schemes.

Even if the different actors were to view carbon payments positively, this would not yet imply the straightforward acceptance of the policy. The acceptance of carbon payments will depend on both the process of developing and agreeing upon the scheme and on how the compensation itself is organized and implemented. To be widely accepted and legitimate, the policies should be seen as fair, treat all actors equally, and be understandable to practitioners. It is also important to realize that during the design and implementation processes of a carbon payment scheme it is possible to influence the perceived acceptability of the policy by having a transparent policy-making process with adequate opportunities to participate and influence the design of the scheme.

A country wishing to implement a carbon payment scheme must take into account its existing legislative framework, which in the case of EU member states includes elements determined at the EU level. Within the EU legislative context, a governmental carbon payment scheme to forest owners would face the challenge of complying with EU state aid rules, as the payments for carbon storage are paid from state resources. This leaves in principle four alternatives for carbon payment scheme implementation: 1. a market-based implementation, 2. the agriculture and forestry block exemption regulation (AFBER), 3. De minimis regulation, and 4. a new aid scheme based on the Commission's new guidelines (GAFSRA) (Table 1).

Fair competition and avoiding market distortions would require that the level of the governmental carbon payments does not exceed the market price of offset units. What makes the legal assessment difficult is the fact that voluntary carbon offset markets are currently either non-existing or undeveloped within the EU. That is, it is not possible – at least for now – to determine the correct market price and whether payments from public funds would in fact be in accordance with market pricing. The AFBER, in turn, does not allow results-based schemes. Hence it seems that the market-based implementation and AFBER are not legally suitable for implementing a carbon payment scheme, at least in the short term.

A carbon payment scheme could, however, be based on the De minimis Regulation, or a new aid scheme. Of these two options, the de minimis approach of paying subsidies of a limited size would likely be the most applicable option in the short term, as the administrative burden is lower, and it does not require a pre-approval by the commission. The de minimis approach to forest carbon payments would be especially suitable where a small-scale private forestry is the prevalent target of the scheme. A new aid scheme through GAFSRA can also be established, but has more limitations regarding eligible costs, requires the European commission's pre-approval, and contains some uncertainties. In the longer term, a wider range of regulatory approaches may become available through the development of the legislative framework within EU as well as in international trade organizations into a direction that fully acknowledges the need for regulating environmental externalities.

8. Conclusions

In a multidisciplinary set-up, we investigated forest carbon payments as a tool to enhance forest-based carbon sinks. This comprehensive approach is novel. We identified several economic, ecological, social, and jurisdictional opportunities and challenges related to the establishment of forest carbon payment schemes. We formulated suggestions regarding the implementation of such schemes in the near term and the long term. The near-term payment scheme tackles the restrictions arising from political institutions and knowledge base but covers only a part of the forest carbon stocks and is based on a low carbon price. The long-term payment scheme, on the contrary, provides correct incentives for optimizing all ecosystem carbon stocks and has greater potential to boost carbon sequestration. However, implementing the scheme requires a deeper understanding of the ecological processes and development in the legislative framework. It is evident that to establish such policies, a close collaboration between policy makers and researchers is necessary.

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