

Dissertationes Forestales 274

**On the optimal regulation of land use sector climate
impacts**

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Academic Dissertation

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Human land use affects the climate through various channels. This thesis focuses on the optimal (i.e. welfare-maximizing) regulation of land use sector climate impacts using market-based instruments, such as taxes and subsidies. The thesis consists of four articles and a summary chapter. Each article focuses on a separate aspect of land use sector climate policy.

The first article outlines a comprehensive tax policy for jointly regulating carbon storage in biomass, soils and products. Considerations regarding soil carbon storage are emphasized.

The second article concerns the regulation of CO₂ emissions from the energy use of logging residues. The harmfulness of these emissions is compared with that of fossil emissions. A way to harmonize the carbon taxation of the both energy sources is presented.

The third article regards the application of the additionality principle to forest carbon subsidies. In the stand-level context it appears that the additionality principle can be implemented without distorting the optimal rotation, by reclaiming subsidies for baseline carbon storage by a site productivity tax on forests. However, at the market-level such a tax distorts the optimal rotation and the optimal land allocation. These distortions can be avoided, if the excess subsidies are eliminated by general land taxation (which also targets other land use).

The fourth article presents a new concept: the Social Cost of Forcing (SCF), which is the social cost of the marginal unit of radiative forcing at a given moment. It is a fundamental price that can be used to value different forcing agents. Forcing agents' prices that are based on the SCF are consistent with the Social Cost of Carbon, and can therefore be consistently applied in cost-benefit analysis or utilized to harmonize the regulation of non-CO₂ forcing agents.

Together the four articles contribute to our understanding of land use sector climate policy design.

Keywords: land use, forest, carbon, climate change, mitigation, climate policy

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Lastly, I wish to thank my family – Katri, Manta and Sohvi – for being there, and my sister Miina for her wise advice now and again.

LIST OF ORIGINAL ARTICLES

- I** Rautiainen A., Lintunen J., Uusivuori J. (2017). Carbon taxation of the land use sector—the economics of soil carbon. *Natural Resource Modeling* 30(2). <https://doi.org/10.1111/nrm.12126>
- II** Rautiainen A., Lintunen J., Uusivuori J. (2018). How harmful is burning logging residues? Adding economics to the emission factors for Nordic tree species. *Biomass and Bioenergy* 108: 167-177. <https://doi.org/10.1016/j.biombioe.2017.11.010>
- III** Tahvonen O., Rautiainen, A. (2017). Economics of forest carbon storage and the additionality principle. *Resource and Energy Economics* 50: 124-134. <https://doi.org/10.1016/j.reseneeco.2017.07.001>
- IV** Rautiainen A., Lintunen, J. (2017). Social cost of forcing: A basis for pricing all forcing agents. *Ecological Economics* 133: 42-51. <https://doi.org/10.1016/j.ecolecon.2016.11.014>

AUTHOR'S CONTRIBUTION

Summary: AR (Aapo Rautiainen) wrote the summary. **Article I:** The authors jointly planned the study. AR contributed to the design of the model and the derivation of the optimal policy. AR was primarily responsible for the writing the article. **Article II:** The authors jointly planned the study. AR conducted the numerical analyses and was primarily responsible for the writing the article. **Article III:** AR participated in the planning of the study and in work on the proofs. AR wrote a preliminary version of the manuscript. **Article IV:** The authors jointly planned the study. AR was primarily responsible for Sections 1 and 3-6, but also participated in the preparation of Section 2.

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INTRODUCTION

Motivation

The global mean temperature has increased by roughly 1°C since pre-industrial times (IPCC 2018). The Paris Agreement aims to limit the warming to 1.5-2°C to reduce the risks and impacts of climate change. Policies to curb climate change are hence needed.

The observed warming is due to an imbalance in Earth's energy budget. Earth absorbs more energy in solar irradiance than it radiates back into space. The trapped energy heats up the planet and its atmosphere. Several factors affect the absorption, emission and reflection of radiation. These factors include e.g. atmospheric greenhouse gas concentrations, aerosols¹, and surface albedo^{2,3}. They can be thought of as a set of internal climate-forcing state variables which together determine the development of the global temperature anomaly under constant external conditions. Controlling them is the key to regulating the climate.

Human activities affect the states of these variables. For example, fossil fuel burning increases the atmospheric CO₂ concentration. Land use activities may increase or decrease the atmospheric concentrations of CO₂ and other GHGs and alter aerosol dispersal and surface albedo (Smith et al. 2014, Myhre et al. 2013). Controlling the climate-forcing variables therefore requires regulating human behavior, which is the main driver behind climate change. This is what climate policy aims to do.

This thesis regards land use sector climate policy. Three aspects are emphasized in the work. First, the approach relies on market-based instruments (e.g. carbon taxes and subsidies), rather than command and control measures or voluntary abatement. Second, the work mostly concentrates on the regulation of CO₂ fluxes (**Articles I-III**). However, in **Article IV** we expand the focus to the consistent pricing (and regulation) of forcing agents and mechanisms besides CO₂. Third, the work primarily concerns forests (**Articles I-IV**). Agriculture is included in the analyses when a complete picture of the whole land use system is needed (**Articles I and III**). Nevertheless, many of the principles that apply to regulating forests' climatic impacts are also applicable to agriculture (**Articles I, II and IV**).

The topic is timely for at least two reasons. First, if the Paris target is taken seriously, global net CO₂ emissions need to be reduced rapidly. The net emissions need to become negative by the latter half of the 21st century (IPCC 2018). This means removing CO₂ from the atmosphere. 'Negative emissions technologies' (NETs) have recently received attention (Nemet et al. 2018, Fuss et al. 2018 and Minx et al. 2018).⁴ Many of them are linked to the land use sector. A comprehensive climate policy (as in **Article I**) is needed to optimally balance climate change mitigation in the land use sector with the rest of the sector's vital

¹ An aerosol is a suspension of solid or liquid particulate matter in the atmosphere. Aerosols affect the absorption and scattering of radiation, and influence climatic processes, such as cloud formation. Most aerosols have a net cooling effect on the climate.

² Albedo is a dimensionless coefficient that indicates the reflective power of a surface. It is defined as the ratio of reflected to incident radiation, and thus receives values between 0 (a perfectly black surface that absorbs all incident radiation) and 1 (a perfectly white surface that reflects all incident radiation).

³ Also clouds affect the absorption, emission and reflection of radiation. However, human land use affects cloudiness indirectly (e.g. via aerosol emissions) rather than directly. Here, we focus on variables that are under direct human control.

⁴ One way to remove CO₂ from the atmosphere is to increase carbon storage in the biosphere by e.g. expanding forest area or altering forest management. Another option is to grow biomass, burn it for energy and capture the CO₂ for permanent storage (BECCS). Options outside the land use sector include e.g. direct air capture (DAC) and ocean fertilization.

functions (such as food and timber production), and with mitigation measures pursued in other sectors.

Second, EU's new 2030 climate and energy framework⁵ includes the regulation of GHG emissions and removals from land use, land-use change and forestry (LULUCF). This extends the coverage of EU climate policy, which has previously excluded land use, and calls for the development of policy measures to mitigate climate change in the land use sector.

The introduction contains two further sections. In the following section, I explain how – and through what physical channels– human activities affect the climate. The section serves as a coarse review to the science that is required to understand the theoretical underpinnings of the policies discussed in this thesis. In the last section, I explain what is meant by welfare-maximizing climate policy. The concept originates from economics and has unifying role in this thesis. The objectives of the thesis and the individual articles are presented in this context. The methods and results are summarized and discussed in the subsequent chapters.

Climatic impacts of land use and fossil fuel combustion

How humans influence the climate

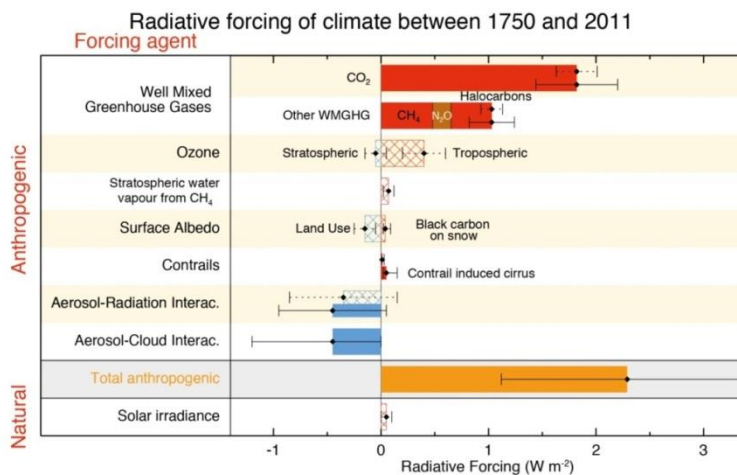


Figure 1. The contribution of different forcing agents (during 1750 to 2011) to anthropogenic and natural radiative forcing in 2011. Solid bars indicate effects that are measured in terms of Effective Radiative Forcing (ERF).⁶ Hatched bars indicate effects that are measured in terms of Radiative forcing. The 5 to 95% confidence range is indicated by the solid lines (for ERF) and dotted lines (for RF). Reprinted from IPCC AR WG1 Chapter 8 (Myhre et al. 2013).

⁵ Covering the years 2021-2030.

⁶ RF is defined as “the change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables such as water vapor and cloud cover fixed at the unperturbed values” (Myhre et al. 2013). ERF is defined as “the change in net TOA downward radiative flux after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged. (Myhre et al. 2013).

Fossil fuel combustion and land use are the main human activities that contribute to climate change. The production and use of fossil fuels emits GHGs, such as CO₂ and CH₄, and aerosols. Land use affects GHG fluxes (CO₂, CH₄, N₂O) and water cycles, emits aerosols and alters the surface albedo (Smith et al. 2014, Myhre et al. 2013).

Radiative forcing (RF) is a measure that can be used to compare different forcing agents' contributions to global warming. It measures the difference between solar irradiance absorbed by the Earth and energy radiated out of the atmosphere back into space. Its unit is Wm⁻². The atmospheric concentrations of three well-mixed GHGs (CO₂, CH₄, N₂O) have increased notably since the onset of the industrial era. Historically, these three gases have contributed most to increase in RF (Fig. 1). Increased aerosol concentrations have had a net cooling impact. Likewise changes in surface albedo, primarily caused by land use change, have had a net cooling effect.

The global carbon cycle

This thesis largely focuses on the regulation of land use sector CO₂ fluxes. The land use sector is connected to the global carbon cycle (Figure 2). Broadly speaking, all terrestrial ecosystems can be considered to be a part of the land use sector, as humans have the potential to decide how the land is used. In this respect, even land set aside for conservation is *used* for that purpose.

Vegetation removes carbon from the atmosphere through photosynthesis. The global gross flux (from the atmosphere into vegetation) is 123 PgC yr⁻¹. This carbon is eventually transferred into soils and then gradually (at least partly) released back into the atmosphere through soil respiration. Altogether soil respiration, fire and net land use change release 119.8 PgC yr⁻¹. As removals exceed emissions, the land sink removes carbon from the atmosphere. The net land flux is 3.2 PgC yr⁻¹.

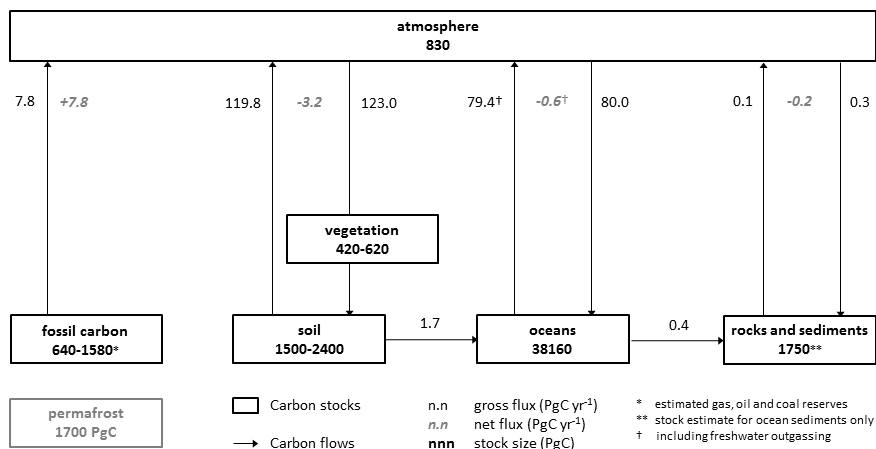


Figure 2. A schematic diagram of the global carbon cycle. Carbon stock estimates (in PgC) are given for the year 2011. The flux estimates (in PgC yr⁻¹) are averages over the 2000–2009 time period. The diagram is a simplified version of Figure 1 in IPCC AR5 WG1 Chapter 6 (Ciais et al. 2013).

Rivers export carbon from soils and weathered rocks into the ocean. Some of it is buried in river and ocean floor sediments. Oceans exchange gasses with the atmosphere. They are a net sink for atmospheric carbon. The net ocean flux is 0.6 PgC yr^{-1} . Volcanism emits carbon into the atmosphere and rock weathering removes carbon therefrom. Put together, these geological processes remove more carbon than they emit. The net geological sink is relatively small: 0.2 PgC yr^{-1} .

Fossil fuel combustion and cement production emit 7.8 PgC yr^{-1} into the atmosphere. This is almost twice as much as is removed by the three natural sinks. Thus, atmospheric carbon accumulates at a rate of 3.8 PgC yr^{-1} , which translates to an 1.8 ppm annual increase in the atmospheric CO_2 concentration.

So far, humans have mainly altered the atmospheric carbon stock by burning fossil fuels and depleting vegetation carbon stocks. Since the onset of the industrial era (ca. 1750) humans have released $365 \pm 30 \text{ PgC}$ by burning fossil fuels and $30 \pm 45 \text{ PgC}$ by depleting vegetation⁷ (Ciais et al. 2013). However, the atmospheric stock has increased by only $240 \pm 10 \text{ PgC}$, as oceans have removed $155 \pm 30 \text{ PgC}$ of the additional carbon (Ciais et al. 2013).⁸

GHG emissions from land use in Finland and the EU

Parties to the Kyoto protocol annually report their emissions to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat. In this reporting the land use sector is divided into two categories: (1) Land Use, Land Use Change and Forestry (LULUCF), and (2) agriculture. The LULUCF sector includes all land uses other than agriculture. The accounting of agricultural soil carbon is also included in the LULUCF sector. Other agricultural GHG emissions from (e.g. fertilizer, cattle and machinery) are accounted to the agricultural sector.

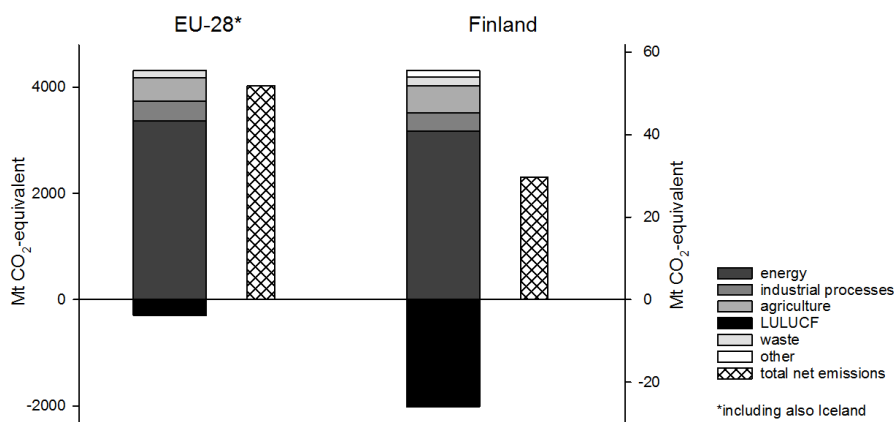


Figure 3. GHG emissions in Finland and the EU. The Scale for Finland's emissions is given on the right. The scale for EU emissions is given on the left. (European Environment Agency 2017, Statistics Finland 2017).

⁷ An estimate of the change in soil carbon stocks is not provided in the same source.

⁸ The atmospheric carbon stock in IPCC's AR5 (Ciais et al. 2013) is given for the year 2011. It is 830 PgC which corresponds to an atmospheric CO_2 concentration of 388 ppm . Since then, the atmospheric concentration has risen by roughly 10 ppm .

The LULUCF sector is a net sink in Finland and in the EU as a whole (Fig 3.). LULUCF sector net removals in Finland (which mostly consist of net removals by forests) equal roughly 47% of emissions from other sectors. The corresponding figure for the entire EU is 7%. In Finland, also the entire land use sector (LULUCF + Agriculture) is a net sink. However, in the EU as a whole, agricultural emissions slightly exceed LULUCF removals and, hence, the sector is an emission source.

The net flow of carbon into the atmosphere can be decelerated (or even reversed) by reducing emissions, increasing removals, or both. Notably, the size of the current land use sector sink (or source) is not necessarily a good indicator of the sector's potential role in climate change mitigation. Even if the sink is small (or even negative), it may still be possible to strengthen it considerably by altering land use and forest management practices.

Objectives of the thesis

This thesis focuses on the optimal regulation of land use sector climate impacts. Here, *optimal* means *welfare-maximizing*. Carbon is emitted from welfare-generating economic activities. However, the emissions cause welfare-reducing climate damage. The damage is an externality of economic activity. Its full value is not taken into account in private production and consumption decisions.

Emitting carbon increases welfare only if the marginal social benefit (MSB) of doing so exceeds the marginal social cost (MSC) of the emission. At the optimum, $MSB=MSC$. The social value of externalities can be internalized into private agents' economic decisions by pricing them accordingly (Pigou 1932). In the case of carbon fluxes, this means taxing emissions and subsidizing removals. The same price is used for emissions from fossil fuel combustion as well as land use carbon fluxes (Tahvonen 1995, Lintunen and Uusivuori 2016).

So far, carbon-pricing has been mostly utilized to regulate fossil emissions. Implemented policies include cap-and-trade systems (such as the EU-ETS) and carbon taxes (such as the CO₂ tax on transport fuels in Finland). Attempts to extend the policy to the land use sector have been less common. Designing a more comprehensive policy, which would also include land use (and potentially also other forcing agents and mechanisms in addition to the most common GHGs), could reduce the costs of climate change mitigation by improving efficiency. The broad objective of this thesis is to outline elements of such a policy. All four articles contribute to the theme.

Article I draws the big picture. The objective of the article is to outline a comprehensive and socially optimal policy for jointly regulating carbon storage in biomass, soils and products. The policy is composed of a set of taxes and subsidies. All carbon fluxes are priced according to Social Cost of Carbon (SCC) in a Pigouvian fashion (Pigou 1932). The policy especially focuses on the regulation of soil carbon stocks in greater detail than previous studies.

Article II has two objectives. The first objective is to assess how harmful CO₂ emissions from burning Nordic logging residues are compared to emissions from fossil fuels. *Harmfulness* is measured in terms of the present value of the caused climate damage. The Effective Emission Factor (EEF) (Lintunen and Uusivuori 2016) is an emission factor that is adjusted to account for the relative harmfulness of the emissions. It enables consistent comparisons between logging residues and fossil fuels. The second objective of the article is to outline how the Pigouvian taxation of residue-based fuels could be harmonized with fossil fuel taxation. This can be done based on the emission factors calculated in the study.

The objective of **Article III** is to analyze whether the additionality principle can be applied in a carbon subsidy system without distorting the optimal outcome. Optimal forest carbon storage can be attained by subsidizing it. Carbon subsidies increase storage. Nevertheless, forests store carbon even if it is not subsidized and subsidizing all carbon storage means also paying for the part which would otherwise be obtained for free. Thus, a regulator may be inclined to apply the additionality principle, i.e. pay for only additional carbon storage. We consider the question at the stand level and at the market level.

The objective of **Article IV** is to present a new concept, the Social Cost of Forcing (SCF). The SCF is the monetary value of the social damage caused by marginal RF at a given instant (Wm^{-2}). Any forcing agent whose temporal decay profile and radiative efficiency are known can be priced based on the SCF. Thus, the concept can be utilized to derive mutually consistent prices for different forcing agents. This allows the inclusion of any type of forcing agents or mechanisms in cost-benefit analysis.

MODELS AND METHODS

All four articles rely on economic models. A mix of analytical and numerical methods is utilized. Different models and techniques are applied in each article.

In Article I, a market-level model is utilized to derive a comprehensive land use sector carbon tax policy. The policy is derived analytically. In Article II, Effective Emission Factors (EEFs) are used to compare the relative harmfulness of CO₂ emissions from the combustion of different logging residue types. Numerical EEF values for different residue types are calculated and compared with the emission factors of other fuels. In Article III, the effects of applying the additionality principle to forest carbon subsidies are analyzed using a stand-level and a market-level model. The results are derived analytically and illustrated with numerical examples. In Article IV, the SCF and mutually consistent prices for different forcing agent types are derived analytically using a stylized integrated assessment model. We also provide numerical examples, in which we utilize the Dynamic Integrated Climate-Economy Model 2013R (Nordhaus and Sztorc, 2013).

These models and methods are reviewed in the following subsections. The only omission is the stand-level model (applied in Article III), which is a generic Faustmann model (Faustmann 1849, Samuelson 1976) that has been extended to include carbon storage (van Kooten et al. 1995). This model is assumed to be familiar to most forest economists, as it is extensively discussed in most forest economics textbooks, such as Amacher et al. (2009).

Market-level models

The market-level models in **Articles I** and **III** are partial equilibrium models. Their basic structure follows the model set-up in Salo and Tahvonen (2004). Salo's and Tahvonen's model depicts the optimization of timber harvests and land allocation between age-structured forestry and an alternative land use. It is an extension of an earlier market-level age-class model without an alternative land use (Mitra and Wan, 1985 & 1986). After Salo and Tahvonen (2004), this model type has been further extended to include forest carbon regulation by Cunha-e-Sá et al. (2013) and Lintunen and Uusivuori (2016),⁹ and carbon and albedo regulation by Rautiainen et al. (2018).

⁹ Also Piazza and Roy (2015) include a generic "stock benefit" which can be interpreted to depict carbon storage.

The original model (Salo and Tahvonen, 2004) is set up as follows. There are n forest age classes. The area of age class s in period t is x_{st} , where $s = 1, \dots, n$ and $t = 0, 1, \dots$. Agricultural area is denoted by y_t . Total land area equals one. Thus, $y_t = 1 - \sum_{s=1}^n x_{st}$.

Harvestable timber volume per hectare is f_s . We assume $0 \leq f_1 \leq \dots \leq f_n$. Let c_t and p_t^c denote the timber harvest and the timber price, respectively. The inverse demand function for timber is $p_t^c = D_c(c_t)$. The economic surplus¹⁰ from timber consumption is $U(c_t) = \int_0^{c_t} D_c(c) dc$. Likewise, the economic surplus from non-forest land use is $W(y_t) = \int_0^{y_t} D_y(y) dy$. The surplus functions are assumed to be continuous, twice differentiable, increasing and strictly concave with respect to their arguments. The discount factor is b .

The optimization problem takes the form

$$v = \max_{\{x_{s,t+1}, s=1, \dots, n, t=0, 1, \dots\}} \sum_{t=0}^{\infty} b^t (U(c_t) + W(y_t)) \quad (1)$$

subject to

$$c_t = \sum_{s=1}^{n-1} f_s (x_{st} - x_{s+1,t+1}) + f_n x_{nt} \quad (2)$$

$$y_t = 1 - \sum_{s=1}^n x_{st} \quad (3)$$

$$x_{s+1,t+1} \leq x_{st} \quad \forall s = 1, \dots, n-1 \quad (4)$$

$$\sum_{s=1}^n x_{s,t+1} \leq 1 \quad (5)$$

$$x_{st} \geq 0, s = 1, \dots, n \quad (6)$$

for all t , and the initial conditions must satisfy $x_{s0} \geq 0, s = 1, \dots, n$ and $\sum_{s=1}^n x_{s0} \leq 1$. The objective is to maximize economic surplus over the infinite time horizon (1). Economic surplus is maximized in the competitive market equilibrium. Thus, the model can be interpreted to depict the competitive market outcome¹¹ (with price-taking producers and consumers with perfect foresight) without externalities. Equation (2) defines the periodic timber harvest as the sum of timber obtained from all clear-cut areas. Notably, in the original formulation of the model it is assumed that the oldest age class is always cut. This assumption is relaxed in **Articles I** and **III**. Equation (3) defines agricultural land as the complement of total forest area. Equation (4) states that land area allocated to age class $s+1$ in the next period cannot exceed the current land area allocated to age class s .

In **Article I**, we interpret the model as a global model, and extend it in several ways. We include multiple land uses in addition to forestry. These land uses are forms of agriculture, and each use produces a distinct agricultural crop. Furthermore, we include (i) the production and consumption of a final good that is produced from different varieties of biomass (timber, crops, residues) and/or fossil inputs (ii) the recycling and landfilling of wastes, and (iii) and an endogenous carbon price. Features (i) and (iii) are also included Lintunen and Uusivuori (2016). The main addition in **Article I**, compared to Lintunen and Uusivuori (2016) is that carbon stocks in biomass, soils and products in more detail. The flow of inputs and carbon in the economy is depicted in Figures 4 and 5.

¹⁰ The model does not include harvesting costs.

¹¹ Economic surplus is maximized in the competitive market equilibrium. Thus, the equilibrium solution can be found by maximizing surplus.

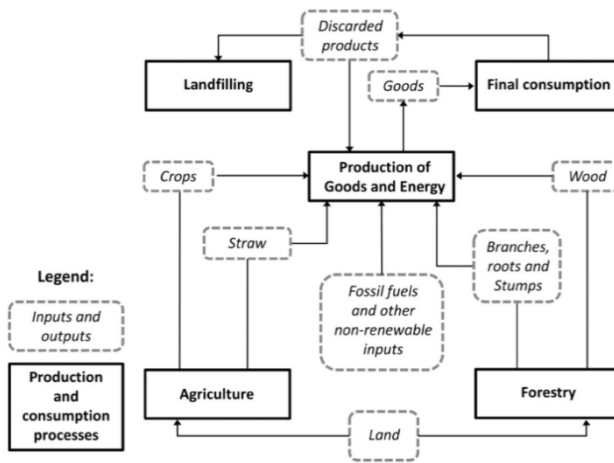


Figure 4. Flow of inputs and outputs in the economy. (Reprinted from **Article I**)

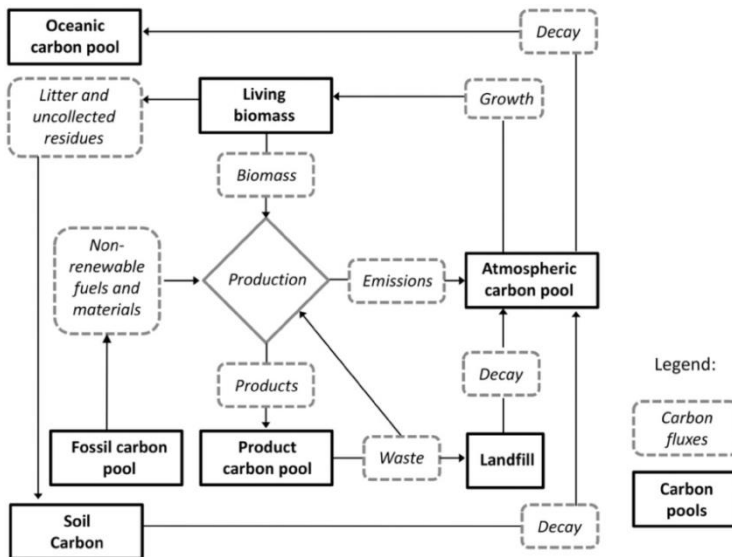


Figure 5. Flow of carbon between carbon pools. (Reprinted from **Article I**)

The aim in **Article I** is to present an optimal policy for regulating carbon storage in biomass, soils and products. To do so, it is first necessary to find the socially optimal outcome in which the carbon externality is fully internalized. (Only then a tax policy can be set up to support the outcome). The optimization problem is set up as follows.

There are n final goods. The quantities of the goods consumed in period t form the set G_t . Gross consumer surplus from consumption is given by the function $V(G_t)$. Total production costs throughout the entire economy are given by the function C_t . Thus, $V(G_t) - C_t$ is net surplus in period t . Let S_t denote the atmospheric carbon stock. The function $\Omega(S_t)$ indicates the monetary value of the disutility caused by the atmospheric carbon stock in period t . We assume that the atmospheric carbon stock is above the

preindustrial level and that additional carbon in the atmosphere is increasingly harmful, i.e. $\Omega' > 0$ and $\Omega'' \geq 0$. The set of choice variables in **Article I** is considerably more extensive than in the model presented by Salo and Tahvonen (2004). In addition to variables depicting land allocation, there are e.g. variables depicting the use of biomass and fossil inputs. Without going into full detail, let Θ_t denote all these variables. Thus, the objective takes the form

$$v = \max_{\{\Theta_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} b^t [V(G_t) - C_t - \Omega(S_t)]. \quad (7)$$

That is, the aim is to maximize the present value of future economic surplus minus the value of the damage caused by atmospheric carbon. The optimization is subject to a large number of constraints that characterize the system pictured in Figures 4 and 5.

To find the optimal solution, we present the Lagrangian of the welfare maximization problem and write the first order necessary conditions for an optimum. From these conditions we infer the monetary shadow values different carbon fluxes. The most important of these is the shadow price of a marginal increase in atmospheric carbon, as it is the Social Cost of Carbon (SCC). The shadow prices of other fluxes, expressed relative to the SCC, form the basis of the optimal carbon tax policy derived in the article. However, the taxes and subsidies in the outlined policy do not directly target the fluxes (which may be difficult to monitor) but rather actions (that are easier to observe).

The model in **Article III** is more parsimonious and its structure is closer to the original model by Salo and Tahvonen (2004). The only note-worthy extension to the original model is that the social value of carbon storage is taken into account in the optimization. Letting τ denote the (time-invariant) social price of CO₂ per cubic meter of wood, and letting Q_t denote the periodic change in stock of timber in forests and wood products, the objective function (1) takes the form

$$v = \max_{\{x_{s,t+1}, s=1, \dots, n, t=0, 1, \dots\}} \sum_{t=0}^{\infty} b^t (U(c_t) + W(y_t) + \tau Q_t). \quad (8)$$

Solving Equation (8) leads to the socially optimal solution. However, in **Article III**, our aim is to study how the implementation of the additionality principle (by taxing forest land¹²) might potentially distort the socially optimal outcome. Thus, in addition to the socially optimal solution, we need to find the solution in which only additional carbon storage is subsidized, and then compare the two.

For this end, we decentralize the market-level model to three price-taking agents: (i) a representative landowner, who produces timber and rents out land,¹³ (ii) an agricultural producer who pays the landowner for land tenure, and (iii) a timber buyer. The representative landowner receives subsidies for carbon storage. However, forest land is also taxed (in a way that eliminates the subsidies for storage that would have occurred anyway). Analyzing the decentralized market equilibrium allows us to conclude that this solution differs from the social optimum and, thus, applying the additionality principle in this way distorts the outcome.

Effective emission factor

The carbon intensity of different fuels is usually compared using emissions factors (gCO₂ MJ⁻¹), which indicate how much CO₂ is emitted per unit of energy released –if the fuels are

¹² Distortions are avoided if the taxation also extends to agricultural land.

¹³ The representative landowner is modelled similarly as in Lintunen and Uusivuori (2016).

combusted. If the fuels are not combusted, the CO₂ is not released. The same is not true for logging residues, which decompose and gradually release CO₂ even if they are not combusted. Thus, constructing comparable emission factors for residues requires establishing how we value the trade-off between current and future emissions. This depends on two things: (i) our rate of discount, and (ii) our expectations regarding the future development of the Social Cost of Carbon (SCC), which indicates how harmful emitting carbon at a given point in time is considered to be. The Effective Emission Factor (EEF) covers these aspects (Lintunen and Uusivuori 2016) and can therefore be used to consistently compare the harmfulness residue-based bioenergy emissions with those from fossil fuel combustion, as is done in **Article II**.

The effective emission factor is derived as follows.¹⁴ Let us consider a batch of residues, with a carbon content equal to 1 CO₂ tonne. The residues are generated at time $s = 0$. Different residue types are distinguished by the subindex i . The function $m_i(s)$ indicates CO₂ emissions from residue decomposition at time s . We assume $\int_0^\infty m_i(s)ds \leq 1$.

Let $p(t)$ denote the SCC. We assume $p(t) = p_0 e^{gt}$, where p_0 is the initial SCC and g is its growth rate. The rate of discount is r . The social cost of releasing 1 CO₂ tonne by burning residues, $c_i(t)$, is

$$c_i(t) = p(t) - \int_0^\infty e^{-rs} p(t+s) m_i(s) ds, \quad (9)$$

which can also be written in the form

$$c_i(t) = \varepsilon_i p(t), \quad (10)$$

where $\varepsilon_i = (1 - \int_0^\infty e^{-ns} m_i(s) ds)$ in which $n = r - g$. Hereafter, we refer to n as the "net discount rate".

Notably, as $c_i(t)$ is the social cost of releasing 1 CO₂ tonne by burning residues and $p(t)$ is the social cost of releasing 1 CO₂ tonne by burning fossil fuels, the factor $\varepsilon_i \in [0,1]$ must express the harmfulness of releasing CO₂ from residues relative to fossil fuels. Three factors affect the value of ε_i : (i) the discount rate, r , (ii) the expected SCC growth rate, g , and (iii) the decay profile of the residues, $m_i(s)$.

The CO₂ emissions per energy unit (e.g. tTJ⁻¹) from fuel combustion are given by the emission factor, γ_j . Hence, the social cost of the CO₂ emissions from releasing one unit of energy by combusting fossil fuel j , SC_j , is

$$SC_j = \gamma_j \times p(t). \quad (11)$$

Likewise, for residues,

$$SC_i = \gamma_i \times c_i(t). \quad (12)$$

The relative "harmfulness" of different fuels can be compared based on the damage caused by their use. Social cost per energy unit is a measure of damage. Traditional emission factors measure impacts (i.e. emissions) rather than damage (i.e. social cost).

¹⁴ The exposition in this section is simpler than in **Article II**. Here, we assume that all emitted carbon is CO₂. In **Article II**, we allow for the possibility that some of the carbon is released as other form (methane, black carbon, etc...).

Nevertheless, the emission factors are often used to compare the *harmfulness* of fossil fuels. This is warranted, as it only requires normalizing SC_j by the carbon price, $p(t)$, which is the same for all fuels. Hence, we obtain

$$\frac{SC_j}{p(t)} = \gamma_j. \quad (13)$$

However, doing the same for residues, we obtain

$$\frac{SC_i}{p(t)} = \gamma_i \times \frac{c_i(t)}{p(t)} = \gamma_i \varepsilon_i. \quad (14)$$

To be able to compare the harmfulness of burning residues versus fossil fuels, it is necessary to scale the residues' emission factors by ε_i . Thus, we obtain the Effective Emission Factor (EEF), $\gamma_i \varepsilon_i$.

In **Article II**, we calculate EEFs for three species (Norway spruce, Scots pine and silver birch) and five residue types (foliage, small branches, large branches, small stems, and stumps) at two sites (Sodankylä in Northern Finland and Hämeenlinna in Southern Finland), with net discount rates ranging from 0% to 10%.¹⁵ The applied net discount rates cover a wide range of possible assumptions regarding the discount rate, r , and the SCC growth rate, g . Soil carbon emissions in the calculations are modelled using the soil carbon model Yasso07 (Tuomi et al. 2011a, Tuomi et al. 2011b). In the calculations, the infinite time horizon is approximated by a 300 year period.

We also demonstrate how the derived factors can be used to harmonize bioenergy carbon taxation with fossil fuel the taxation. Bioenergy taxes (per energy unit) obtained by multiplying the SCC by the EEF of the fuel are consistent with the comprehensive tax policy outlined in **Article I**.

Integrated Assessment Model structure

The Social Cost of Carbon (SCC) depicts the marginal social cost of emitting one tonne of CO₂ at a given point in time. It is usually estimated using Integrated Assessment Models (IAMs) such as DICE (Nordhaus 1993), FUND (Tol 1997) and PAGE (Hope et al. 1993). “Integrated” means that the model contains two components (‘the climate’ and ‘the economy’) and that their interaction is taken into account.

In **Article IV** we present a novel concept, the Social Cost of Forcing (SCF), which can be used to derive a price for any forcing agent in a similar fashion –as long as the agents temporal decay profile and radiative efficiency are known. Like the SCC, the SCF can be estimated using IAMs. In this section, I outline the fundamental basic structure of a “DICE-like” IAM and explain how the SCC and SCF are derived.

Climate

Human activities contribute to radiative forcing through many channels. Technically, these channels can be characterized by stock variables and flow variables. Stock variables can be used to describe stock pollutants, such as greenhouse gases like CO₂ and CH₄. Flow

¹⁵ Also three alternative climate scenarios (constant climate, weak climate change and strong climate change) were considered, as climate affects the decomposition of residues. However, as climate change had relatively little impact on the EEFs, these results are not discussed in this summary.

variables can be used to describe other forcing mechanisms which contribute to radiative forcing transiently. Surface albedo is an example of such a mechanism.

Stock pollutants accumulate in the atmosphere. Emissions, $E_i(t)$, add to the atmospheric stock, $S_i(t)$, of each pollutant i . The atmospheric stocks of all n relevant pollutants are summarized as $\mathbf{S}(t) = \{S_1(t), \dots, S_n(t)\}$. Each stock decays naturally at the rate δ_i . Stock changes are driven by emissions and decay,

$$\dot{S}_i(t) = E_i(t) - \delta_i S_i(t). \quad (15)$$

Unlike stock variables, which contribute to radiative forcing through their stocks, transient forcing mechanisms have a direct impact. Thus, they are best described by flow variables, X_j . The states of all m climate-forcing flow variables are summarized as $\mathbf{X}(t) = \{X_1(t), \dots, X_m(t)\}$. The functions $F_S(\mathbf{S}(t))$ and $F_F(\mathbf{X}(t))$ indicate radiative forcing caused by stock and flow variables, respectively. $F(t)$ is total radiative forcing. Hence,

$$F(t) = F_S(\mathbf{S}(t)) + F_F(\mathbf{X}(t)). \quad (16)$$

Radiative forcing affects the global mean temperature, $T(t)$. The change in global mean temperature, $\dot{T}(t)$, is determined as a function of total radiative forcing, $F(t)$, and the current global mean temperature, $T(t)$, i.e.

$$\dot{T}(t) = f(F(t), T(t)). \quad (17)$$

Thus,

$$T(t) = \int_{-\infty}^t \dot{T}(t) dt. \quad (18)$$

Economy

The economy produces and consumes a single final good. The good is produced from inputs $\mathbf{E}(t)$ and $\mathbf{X}(t)$ by utilizing capital $K(t)$. $\mathbf{E}(t)$ are inputs that cause emissions (e.g. CO₂). $\mathbf{X}(t)$ are inputs that contribute to radiative forcing through other mechanisms (e.g. surface albedo).¹⁶ The production function for the final good is $Y(t)$. However, its output is reduced by global climate damage. We assume $Y'(T) < 0$.

$$Y(t) = Y(\mathbf{E}(t), \mathbf{X}(t), K(t), T(t)). \quad (19)$$

Let $C(t)$ denote total consumption at time t , respectively. Let $I(t)$ denote investments. The macroeconomic accounting identity states that

$$Y(t) = C(t) + I(t). \quad (20)$$

That is, all output net of production costs is either consumed or invested. Investments and depreciation determine the change in the capital stock.

$$\dot{K}(t) = I(t) - \delta_K K(t) \quad (21)$$

¹⁶ To simplify the exposition we exclude other inputs, such as labor.

Let W denote welfare, which we define as the net present value of the total utility flow derived from consumption. The function $U(C(t))$ indicates utility derived from consumption. We assume that $U' > 0$ and $U'' < 0 \forall C$. The pure rate of time preference is $r > 0$. The regulator's objective is to maximize welfare over an infinite time horizon, i.e.

$$\max_{E(t), X(t), I(t)} W = \int_0^{\infty} e^{-rt} U(C(t)) dt \quad (22)$$

subject to (15)-(21). The current value Hamiltonian of the dynamic optimization problem is:

$$\begin{aligned} H = & U(C(t)) \\ & + \mu_K(t)(I(t) - \delta_K K(t)) \\ & + \mu_T(t)f(F(t), T(t)) \\ & + \sum_i \mu_{S_i}(t)(E_i(t) - \delta_i S_i(t)) \\ & + \lambda_F(t)(F(t) - F_S(\mathbf{S}(t)) - F_F(\mathbf{X}(t))) \end{aligned} \quad (23)$$

where

$$C(t) = Y(\mathbf{E}(t), \mathbf{X}(t), K(t), T(t)) - I(t). \quad (24)$$

The optimal temporal trajectories for $I(t)$, $E_i(t)$, and $X_j(t)$ are characterized by the first order conditions

$$-U' + \mu_K(t) = 0, \quad (25)$$

$$U' Y'_{E_i(t)} + \mu_{S_i}(t) = 0, \quad (26)$$

and

$$U' Y'_{X_j(t)} - \lambda_F(t) F'_{X_j(t)} = 0, \quad (27)$$

respectively. In Equation (25) $-U'(t) < 0$ is the marginal cost of investment (i.e. the marginal decrease in current utility, when a unit of output is invested rather than consumed) and $\mu_K(t) > 0$ is the marginal benefit of investment (i.e. the shadow value of capital). Thus, the equation states that the marginal benefit must equal marginal cost at every point in time. Likewise, Equations (26) and (27) state that the marginal benefits from input use must equal marginal costs. The first terms on the left-hand side (LHS) of (26) and (27) indicate the benefits, i.e. the utility from increased consumption. The second terms indicate the costs, i.e. the value of the climatic damage. In Equation (26), $\mu_{S_i}(t) < 0$, is the shadow value of increasing the atmospheric stock of a given pollutant. In Equation (27), $\lambda_F(t)$, is

the shadow value of a transient increase in radiative forcing.¹⁷ (It should be noted, that at this stage all three shadow values, μ_K , μ_{S_i} and λ_F , are expressed in “utils” rather than monetary units.)

Applying the maximum principle we obtain the optimality conditions for capital, temperature and atmospheric pollutant stocks. They are

$$\dot{\mu}_K(t) = -\frac{\partial H}{\partial K} + r\mu_K = (r + \delta_K)\mu_K(t) - U'Y'_K, \quad (28)$$

$$\dot{\mu}_T(t) = -\frac{\partial H}{\partial T} + r\mu_T = (r - f'_T)\mu_T(t) - U'Y'_T, \quad (29)$$

and

$$\dot{\mu}_{S_i}(t) = -\frac{\partial H}{\partial S_i} + r\mu_{S_i} = (r + \delta_i)\mu_{S_i} + \lambda_F(t)F'_{S_i}, \quad (30)$$

respectively. Equations (28)-(30) allow us to tackle two central questions in intertemporal climate policy. The first is discounting, i.e. how should we weight the costs and benefits that occur at different points in time? The second is the social cost of stock pollutants, i.e. what is the social cost of emitting the marginal tonne of CO₂ and how does it change over time?

Equation (28) helps us address discounting. From equation (25), we know that $\mu_K = U'$ and, thus, also $\dot{\mu}_K = U''\dot{C}$. Utilizing this information and reorganizing Equation (28) we obtain

$$Y'_K - \delta_K = r - \frac{U''\dot{C}}{U'}. \quad (31)$$

The LHS of Equation (31) is the net return on marginal capital, which is more commonly known as the real interest rate. The first term on the right-hand side (RHS) is pure rate of time preference. The second term is the relative temporal growth rate of marginal utility from consumption ($U''\dot{C}/U' < 0$, when $\dot{C} > 0$). In other words, Equation (31) is the Ramsey formula for discounting formula (which is common in climate economics). Often, however, the formula is presented in a simpler form, which is obtained when U is assumed to be a CRRA utility function.¹⁸ Below, we interpret the equation using this formulation (which can be found in e.g. Arrow et al. 2012).

Let \bar{r} denote the real interest rate. Let η denote the elasticity of the marginal utility of consumption in the CRRA utility function. Let g denote the consumption growth rate. The Ramsey formula is

$$\bar{r} = r + \eta g. \quad (32)$$

Equation (32) shows, that the real interest rate (which measures the required return on investments) is higher than the pure rate of time preference. The difference is explained by economic growth (i.e. growth in consumption). Assuming that $c' > 0$, $U' > 0$, and $U'' < 0$,

¹⁷ $\frac{\partial H}{\partial F(t)} = \lambda_F(t) + \mu_T(t)f'_{F(t)} = 0 \Leftrightarrow \lambda_F(t) = -\mu_T(t)f'_{F(t)}$, where $\mu_T < 0$.

¹⁸ CRRA stands for Constant Relative Risk Aversion. In this case, $U = \begin{cases} \frac{c^{1-\eta}-1}{1-\eta} & \eta \neq 1 \\ \ln(c) & \eta = 1 \end{cases}$.

a marginal unit of consumption in the future generates less utility than marginal consumption today. Thus, to justify forgoing consumption today to pay for an investment, its return must be high enough to compensate for the decline in the marginal utility of consumption.

Equation (30) helps us understand the social cost of stock pollutants, such as CO₂. As Equation (30) is a first-order linear differential equation, μ_{S_i} can be solved by applying the integrating factor method. We obtain

$$\mu_{S_i}(t) = \int_0^\infty e^{-\delta i v} F_{S_i}'(t+v) \lambda_F(t+v) e^{-rv} dv, \quad (33)$$

where $\mu_{S_i}(t)$ is the social cost of pollutant i measured in utils. Two adjustments are needed to convert the utils into monetary units. First, the shadow value of marginal radiative forcing (measured in utils), $\lambda_F(t+v)$, must be converted into shadow price (measured in monetary units), $\bar{\lambda}_F(t+v)$, so that $\bar{\lambda}_F = \lambda_F/U'$. Second, as the social cost is now measured in monetary terms, the real interest rate, $\bar{r}(t)$, must be applied for discounting (instead of the pure rate of time preference, r). Hence; we obtain

$$SC_i(t) = \int_0^\infty e^{-\delta i v} F_{S_i}'(t+v) \bar{\lambda}_F(t+v) e^{-\bar{r}(v)v} dv, \quad (34)$$

where $SC_i(t)$ denotes the social cost of pollutant i in monetary terms (e.g. euros per emitted CO₂ tonne). The RHS of the equation is interpreted as follows. $e^{-\delta i v}$ signifies the share of the emission pulse remaining in the atmosphere at time v after the pulse is emitted. F_{S_i}' is marginal impact of the pollution stock on radiative forcing at time $t+v$. $\bar{\lambda}_F$ is the social cost of a marginal unit of radiative forcing at time $t+v$, which $e^{-\bar{r}(v)v}$ discounts to its present value. Thus, $SC_i(t)$ is present value of the social damage caused by the emission pulse during the time it resides in the atmosphere.

Notably, the social cost of a marginal unit of radiative forcing in Equation (34), $\bar{\lambda}_F$, is a fundamental price that can be used to derive a price for the pulse emission of any stock pollutant. The same fundamental price can also be used to value transient forcing agents and mechanisms. The universality of the Social Cost of Forcing as a fundamental price for all forcing agents is the central observation made in **Article IV**.

SUMMARIES OF ARTICLES

I. Carbon taxation of the land use sector – the economics of soil carbon

We outline a comprehensive socially optimal tax policy for jointly regulating carbon storage in biomass, soils and products. The policy is based on Pigouvian principles, i.e. carbon fluxes are priced according to their social value. The presented policy is not a unique way to incentivize optimal carbons storage. Other ways of taxing emissions and subsidizing removals also lead to the optimal outcome, as long as all carbon fluxes are fully covered and optimally priced (Lintunen and Uusivuori 2016, Lintunen et al. 2016). We present a solution that is based on pricing fluxes rather subsidizing the maintenance of carbon stocks, but take into account the challenges of implementing such a policy in practice. Therefore, the applied taxes and subsidies do not directly target the fluxes (which may be difficult to monitor) but actions (that are easier to observe). We especially focus on the regulation of soil carbon stocks, which has not been previously done in similar detail.

The policy consists of incentives to regulate land use and input use. The taxes and subsidies for land use are measured in € ha⁻¹ yr⁻¹. Land use is regulated by four kinds of incentives. (1) There is an annual, stand-age-dependent subsidy for standing forest. The subsidy equals the (monetary value of) the social benefit of carbon removal from the atmosphere through growth during the year minus the social cost of future emissions from the decay of litter generated during the year. The sum of these two components is (usually) positive. (2) There is a stand-age-dependent tax on clear cuts. The tax takes into account (i) the social cost of future emissions from the decay of the felled biomass, given that it is left to decay on site, (ii) the estimated social benefit of carbon removal from the atmosphere through growth during the year when the stand is cut, and (iii) the estimated social cost of future emissions from the decay of litter generated during that year. The monetary value of the sum of all three components is (usually) negative. The tax is collected in the year that the stand is cut. (3) Agricultural land use is subsidized. The annual subsidy takes into account (i) the social cost of future emissions from the decay of the biomass yield, given that it is left to decay on site, (ii) the social benefit of carbon removal from the atmosphere through growth during the year, and (iii) the social cost of future emissions from the decay of litter generated during the year. The monetary value of the sum of all three components is slightly positive. (4) Land use conversions may be taxed or subsidized, depending on how the conversion alters the decay of existing soil carbon stocks and, thus, the social cost of the future soil carbon emissions. Conversions, that accelerate (decelerate) the release of soil carbon, are taxed (subsidized). The tax or subsidy is administered in the year that the land use is converted.

The taxes and subsidies for input use are measured in € t⁻¹. Input use is regulated by three kinds of incentives. (1) Non-renewable (fossil) input use is taxed. The tax consists of (i) the social cost of the carbon emissions that occur during the production process, and (ii) the present value of the social cost of the emissions future emissions that occur when the products decompose in landfills. (2) Renewable (biomass) input use may be taxed or subsidized. The tax/subsidy consists of (i) the social benefit of decay emissions that are avoided as the felled biomass is not left to decompose in the forest/field, (ii) the social cost of the carbon emissions that occur during the production process, and (iii) the present value of the social cost of the emissions future emissions that occur when the products decompose in landfills. Input use is subsidized (taxed) if the carbon from the biomass inputs is released more slowly (faster) than through natural decay in the forest or field. (3) The energy use of discarded products is taxed, as burning the waste accelerates the release of carbon (compared to landfilling). The tax is composed of two parts: (1) the social cost of the carbon emissions from combustion, and (2) the social benefit of avoided future emissions from product decay in landfills.

II. How harmful is burning logging residues? Adding economics to the emission factors for Nordic tree species

We compare the relative harmfulness of CO₂ emissions from burning Nordic logging residues for bioenergy to corresponding emissions from fossil fuels and peat. The social cost of the resulting carbon emissions is used as a measure of the harmfulness of the emissions. The comparisons between logging residues and other fuels are based on Effective Emission Factors (EEF).

We calculate EEFs for three species (Norway spruce, Scots pine and silver birch) and five residue types (foliage, small branches, large branches, small stems, and stumps) at two sites (Sodankylä in Northern Finland and Hämeenlinna in Southern Finland), in three climate scenarios (constant climate, weak climate change and strong climate change), and

with net discount rates ranging from 0% to 10%. The net discount, n , rate is the discount, r , minus the SCC growth rate, g . Thus, the applied net discount rates cover a wide range of possible assumptions regarding r and g . Soil carbon emissions in the calculations are simulated using the Yasso07 soil carbon model (Tuomi et al. 2011A, Tuomi et al. 2011B). The infinite time horizon is approximated by a 300 year period.

Four general observations can be made. (1) Small residues (i.e. branches and foliage) have systemically lower EEFs than large residues (i.e. stems and stumps). (2) The net discount rate, n , has a strong impact on the EEFs: the lower the n , the lower the EEF. (3) Burning any kind of residues is less harmful than burning peat or coal, regardless of the net discount rate (in the given range). (4) The comparison between residues and natural gas is more sensitive to the net discount rate. The EEFs for foliage and small branches are systematically lower than the emission factor of natural gas. However, the EEFs of large branches, stems and stumps may be higher or lower than the emission factor for natural gas, depending on the net discount rate

We also demonstrate how the CO₂ taxation of logging-residue-based bioenergy can be harmonized with the taxation of fossil fuels. The optimal tax for CO₂ emissions from fossil fuel burning is equal to the SCC, which reflects the monetary value of the damage caused by the emissions. Thus, the optimal tax per energy per energy unit is obtained by multiplying the SCC by the emission factor (EF) of the given fuel. However, for residues the EEF is used instead of the EF. This adjusts the tax on the emissions according to their relative harmfulness. The tax on small residues is lighter than the tax on large residues. Residues in general are (usually) more lightly taxed than most fossil fuels.

III. Economics of forest carbon storage and the additionality principle

Optimal carbon storage in forests can be attained by pricing forest carbon fluxes according to their social value, i.e. subsidizing carbon storage. Carbon subsidies increase storage. Nevertheless, forests also store carbon even if it is not subsidized and, therefore, pricing all carbon fluxes means also paying for carbon storage that would otherwise be obtained for free. This can be expensive. Thus, a regulator may be inclined to apply the additionality principle, i.e. pay for only additional carbon storage. We analyze whether the additionality principle can be applied in a carbon subsidy system without distorting the optimal outcome. The question analyzed at the stand level and at the market level.

We show that in the stand-level context (it seems that) the additionality principle can be applied without distorting the optimal rotation. This can be done by subsidizing all carbon storage and levying a site productivity tax, which eliminates subsidies for baseline carbon storage. The present value of the tax receipts equals the present value of carbon storage when it is not subsidized.

At the market-level, however, carbon subsidies also affect land allocation in addition to the timing of harvests. We study the impacts of the subsidies by comparing steady-state outcomes. First, we characterize the optimal steady-state forest rotation period, age-class structure, and land allocation. Notably, the optimality conditions differ depending on whether carbon storage is subsidized or not. Thus, both the optimal rotation and the optimal land allocation may differ in the two outcomes. Moreover, when carbon storage is subsidized, it may be optimal to allocate a portion of the forests to carbon storage only.

Then we decentralize the social planning problem and characterize the optimal steady-state solution in the case in which land is owned by a private landowner, carbon storage is subsidized, and the additionality principle is applied by levying a site productivity tax on forests. We show that the regulated market-equilibrium (when the additionality principle is applied to carbon subsidies) differs from the social optimum and, therefore, site

productivity taxation distorts the outcome. Nevertheless, this distortion can be avoided if also agricultural land is subjected to the taxation – in addition to forests.

Our numerical examples suggest that although applying the additionality principle to carbon subsidies causes distortions (when excess subsidies are eliminated by taxing forest land only), the policy may still be successful at increasing carbon storage (compared to the baseline) and reducing regulatory costs (compared to subsidizing all carbon storage). We also compare the policy's performance to two other second-best policies, namely (i) subsidizing afforestation and taxing deforestation, and (ii) subsidizing wood production. When the three policies are designed so that they all yield the same steady-state carbon storage¹⁹, carbon subsidies with the additionality principle appears to outperform its rivals in terms of welfare effects and regulatory costs.

IV. Social Cost of Forcing: a basis for pricing all forcing agents

We present a new concept, the Social Cost of Forcing (SCF), which is the monetary value of the social damage caused by marginal RF at a given instant (Wm^{-2}). The SCF is a fundamental price that can be used to derive a specific price for any forcing agent or mechanism, whose temporal decay profile and radiative efficiency are known. These prices are mutually consistent. Thus, the method enables the inclusion of multiple forcing agents of any kind in cost-benefit analysis.

We first motivate the concept with the help of a stylized global Integrated Assessment Model (IAM). We use the model to derive an expression for the SCF, and show how prices for different forcing agents and mechanisms can be expressed in terms of the SCF. Such prices can be derived for pulse emissions (such as CO_2 and CH_4) as well as factors that contribute to radiative forcing transiently (such as surface albedo).

We also present the concept of Social Cost Ratio (SCR), which can be used to compare the harmfulness of emissions of different GHGs at any given point in time. As the SCR is based on consistent social prices of GHG pulses, it is the economic analog of the Global Warming Potential (GWP) (Lashof and Ahuja 1990), which is often used for such comparisons. However, the SCR measures relative damage, whereas GWP measures cumulative radiative forcing.

We illustrate our findings with numerical examples which rely on the DICE model (version 2013R, see Nordhaus and Sztorc (2013)). We derive an SCF trajectory and then calculate SCF-based prices for CO_2 , CH_4 , and the surface albedo of a Norway spruce stand. Furthermore, we calculate the SCR of CH_4 to CO_2 . We show that the SCR (i) changes over time, and (ii) its value differs from the GWP. The SCR trajectory for the next hundred years falls between the GWP_{20} and GWP_{100} provided for CH_4 in IPCC's AR5.

DISCUSSION

Requirements and limitations of a comprehensive policy

Regulating land use sector carbon storage through taxation requires an ability to accurately monitor carbon fluxes. Also, functioning institutions are needed. The tax system must be reliable and an up-to-date register of land ownership is needed to allocate the payments to the right people. Property rights need to be clearly defined and respected to ensure that landowners can optimize the use of their resources. In these respects, industrialized

¹⁹ In the example, all three policies were required to generate the same level of steady-state carbon storage as in the socially optimal outcome (i.e. when carbon storage is fully subsidized).

countries may be readier to implement the policy than some developing countries. The policy therefore has better prospects of being first implemented regionally, rather than globally. However, regional implementation may lead to carbon leakage. That is, e.g. reducing timber harvests in one region with a strict climate policy may shift the harvests to another region with laxer regulation. Hence, if the policy is implemented regionally, there may be a need for additional measures (such as carbon tariffs) to curb carbon leakage.

In **Articles I-III**, we focus on the regulation of carbon fluxes. However, land use also affects the climate through various other channels. A comprehensive climate policy should also seek to regulate these impacts. Failing to do so may lead to a socially suboptimal outcome when other forcing agents' impacts are non-negligible and do not cancel out. Rautiainen et al. (2018) illustrate this point by focusing on the joint regulation of forest carbon and landscape albedo. The study shows that carbon pricing alone may lead to the overprovision of climate benefits at the expense of food and timber production. Complementing the policy with albedo pricing reduces these welfare losses and, therefore, increases welfare. The full inclusion of other forcing agents (e.g. aerosols) remains a challenge for future research. The SCF method outlined in **Article IV** provides a basis for pricing these forcing agents.

Policies must be politically acceptable to be implementable. In a democracy, politicians' and voters' views determine whether a policy is acceptable. Expensive policies (in terms of increased public spending and taxes) are usually more difficult to justify to the public than inexpensive ones. From the regulator's point of view, setting up a publicly funded forest carbon subsidy scheme in a highly forested country, such as Finland or Sweden, could be expensive. Subsidizing all carbon storage (as proposed in **Article I**) may therefore not be politically acceptable. However, applying the additional principle to the subsidies (as proposed in **Article III**) could notably reduce public spending and make the policy more acceptable.

Alternative policy designs

Comprehensive policies

As noted in **Article I**, there are various alternative ways to regulate land use sector emissions which also lead to the optimal outcome, as long as all carbon fluxes are fully covered and optimally priced (Lintunen and Uusivuori 2016). Here, I present two examples of the alternative policy structures following Lintunen et al. (2016A).

The first policy is based on the pricing of carbon fluxes. Thus, the way forest carbon storage is subsidized resembles the approach applied in van Kooten et al. (1995) and Hoen and Solberg (1997). Otherwise, the incentives are structured as in **Article I**, except carbon storage after harvest (e.g. in products and landfills) is treated differently. In the following, I refer to this system as *flow regulation*. The second policy is based on the carbon rent concept, which means subsidizing the maintenance of stocks (rather than directly pricing fluxes, as in the previous case). Thus, the way in which forest carbon storage is subsidized resembles the approach applied by e.g. Sohngen and Mendelsohn (2003), Sedjo and Marland (2003), and Uusivuori and Laturi (2007). In the following, I refer to this system as *stock regulation*. Lintunen et al. (2016B) show that both systems incentivize identical landowner behavior, given that the incentives are suitably designed.

The two systems are presented in Figure 6 and Table 1. Figure 6 is a stylized schematic of the relevant parts of carbon cycle. The numbers 1-4 indicate the parts of the carbon cycle that are regulated. Table 1 contains a description of the policy instruments that are used to regulate each part.

Table 1. Alternative ways to structure incentives for carbon storage

	Flow regulation	Stock regulation
① Land use	The landowner receives an annual subsidy based on the net change in the amount of carbon stored in vegetation and soils. In practice, this means fully subsidizing carbon removals and taxing harvests as if the carbon were released immediately.	The landowner is paid an annual subsidy (i.e. “carbon rent”) for maintaining the carbon stock in biomass and soils. The size of the subsidy depends on (i) the size of the carbon stock, (ii) the interest rate, and (iii) the carbon price.
② Products	Biomass utilization is subsidized. The subsidy is based on the carbon content of the biomass. Similarly, the discarding of products is taxed. The tax is based on the carbon content of the products. The emissions are valued as if all carbon were released immediately, when the products are discarded.	The owners of carbon-containing products, such as wooden buildings, are paid carbon rent.
③ Waste	Landfilling and geological disposal of waste is subsidized according to its carbon content and the duration of the storage.	Maintaining landfills and geological deposits is subsidized by paying carbon rent, which depends on the size of the maintained carbon stock.
④ Combustion	Fossil input use emissions are taxed. Biomass use emissions are not taxed, as the tax has already been paid, regardless of its source. Newly harvested biomass is taxed at harvest (as if the carbon were released immediately) Recycled biomass is taxed when the products are discarded for recycling.	Fossil input use emissions are taxed. Biomass use emissions are not taxed.

In **Article I**, we focus on the regulation of biomass production. The regulation of consumer behavior is depicted only crudely. All emissions from refining the biomass into goods, consuming the goods, and finally discarding and potentially landfilling them are regulated by a single input tax. The tax is paid when the goods are produced. Thus, as we note in the article, the proposed regulation does not fully regulate consumer behavior. For example, consumers’ discarding decisions are omitted from the analysis (and constant discard rates are assumed). Nevertheless, in real life, consumer behavior affects discard rates, as consumers decide when to replace old goods with new ones. Regulatory precision in guiding consumer behavior could therefore be improved by regulating discarding and waste management decisions separately, as is done by the alternative policies presented in Figure 6 and Table 1.

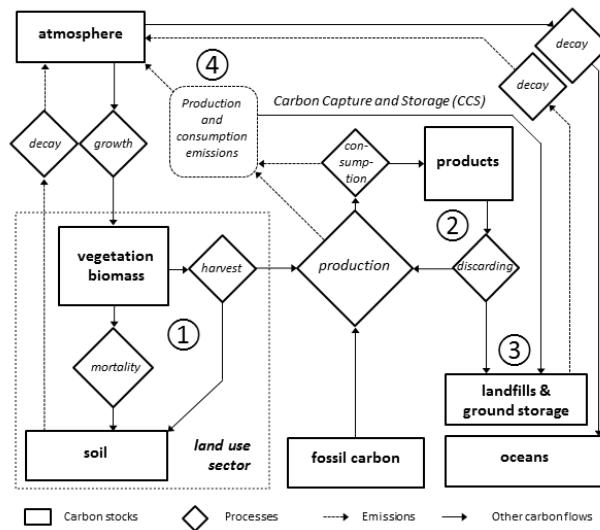


Figure 6. The carbon cycle, economic activity and the regulation of carbon storage (adapted from Lintunen et al. 2016A)

Bioenergy taxation

As there are various ways to (consistently and comprehensively) organize land use sector carbon taxation, the optimal tax treatment of bioenergy depends on how the rest of the incentives are structured.

In **Article II**, we propose taxing bioenergy according to the social value of the damage that is caused by bringing forth the release of carbon from slowly decaying residues (i.e. releasing the carbon now, rather than later). This approach is consistent with a broader system, in which the forest owner is (i) paid for removals, and (ii) taxed for future emissions from residues when they are generated. The tax equals the present value of the damage caused by the future emissions, assuming that the residues are left to decay on site. In other words, the taxation is structured as in **Article I**. This system regulates emissions correctly, regardless of whether the residues are left on site or burned. If the residues are left on site, the land owner pays for the emissions from decomposition. If the residues are burned, the user of the residues is pays a tax that corresponds to only the incremental damage that is caused by speeding up the release of carbon. Double-taxation is thus avoided.

An alternative way to organize the incentives would be to (i) pay the landowner for removals (ii) tax all carbon in felled biomass as if it were released immediately (iii) subsidize leaving the residues on site, and (iv) treat the energy-use of residues as emission-free (in taxation).²⁰ Such a system would incentivize similar behavior as the previous one. It would also leave the landowners' and biomass users' incomes unchanged, as changes in the price of biomass would compensate for the changes in taxation. While landowners would face higher taxes, they would also receive a higher price for biomass. Likewise, while

²⁰ Components (i) and (ii) could alternatively be replaced by paying carbon rent to the landowner, based on the amount of carbon stored in living biomass.

biomass users would have to pay a higher price for the residues, they would avoid being taxed for burning them.

European Union's climate policy

LULUCF regulation

In the European Union, land use sector climatic impacts are mostly covered the Land Use, Land Use Change and Forestry (LULUCF) regulation (The European parliament and the Council of the European Union, 2018).²¹ The regulation defines the land use sector emission reduction targets and outlines the principles according to which changes in emissions and removals may be accounted towards the target. The regulation was recently updated for the years 2021-2030.

The LULUCF regulation covers the accounting of net carbon stock changes in cropland, grassland, forests, and harvested wood products.²² The additionality principle is applied in the accounting. That is, stock changes during the commitment period are compared to a predefined reference level. Only the deviation from the reference level is accounted. The accounting is first done separately for each land use class. Then totals are summed to obtain the grand total for the entire LULUCF sector.

The reference levels for cropland, grassland and wetlands are based on average annual base- period (2005-2009) emissions. The reference levels for forests²³ are “based on the continuation of sustainable forest management practice and intensity, as documented between 2000-2009 with regard to dynamic age related forests characteristics in national forests” (Article 8).²⁴ Generally, forests in EU countries are carbon sinks, which means that the forest generate net removals. The forest reference levels are set accordingly, i.e. annual net removals are expected during the coming decade. If the net removals during the commitment period fall short of the reference level, the difference is fully accounted as emissions. However, if the removals exceed the reference level, the accounting of the excess removals (as negative emissions) is restricted by a cap. The cap equals 3.5% of each member state's base-year emissions times the length of the commitment period in years.

The accounting of increased carbon storage in harvested wood products is not subject to this limitation. Net carbon stock changes for three categories of harvested wood products are accounted. These categories are: paper, wood panels and sawn wood. Biomass combustion is considered emission free, as the emissions are already accounted when the biomass is removed from the forest.²⁵

The LULUCF sector (as a whole) has a “no-debit” rule: accounted net emissions may not (officially) exceed zero. However, member states may generate excess removals and, if they do, there are certain *flexibilities* that allow them to benefit of these removals up to a certain degree. Excess LULUCF removals may be transferred (i.e. sold) to other member

²¹ Other sectors of the economy are regulated by the Emissions Trading System (EU ETS) and the Effort Sharing Regulation (ESR). The EU ETS covers most emissions from power and heat generation, energy-intensive industries and commercial aviation. The ESR covers emissions from energy, industrial processes, product use, agriculture and wastes that are not regulated by the ETS (e.g. transport and construction). Notably, although the ESR covers some emissions from agriculture, soils and biomass are covered by the LULUCF regulation.

²² Additionally, member states may voluntarily include wetlands and settlements.

²³ Here, ‘forests’ refer to forest land remaining forest land’. Emissions and removals from afforestation and deforestation are accounted separately from carbon stock changes in other forests. Thirty years after its conversion afforested land is considered ‘forest land remaining forest land’.

²⁴ Additional guidance for determining forest reference levels is provided in Annex IV of (The European parliament and the Council of the European Union, 2018)

²⁵ as advised in the IPCC good practice guidelines (Aalde et al., 2006)

states, banked for future years (during the commitment period), or transferred to the ESR sector. Transfers to other member states are not restricted. However, banking and transfers to the ESR sector are restricted by national caps.

If a country's LULUCF sector emissions exceed zero, the excess emissions are accounted in the ESR sector. Thus, a country that is unable to meet its LULUCF sector target may transfer a part of the reduction burden to the ESR sector. Although this property of the regulation is not an official flexibility, it works in a similar way.

Lastly, there is a managed forest land flexibility which constitutes a “conditional easing” of the forest reference level. A member state may use this flexibility if (1) the European Union as a whole meets its no-debit target for the LULUCF sector, but (2) the member state does not meet its own target, despite the fact that its forests are a carbon sink²⁶. In this case, an additional quantity of removals is subtracted from the country's (accounted) net emissions. The quantity is predetermined and limited, and is granted for free (i.e. without requiring further emission reductions).

LULUCF regulation in the context of this thesis

Forest carbon storage can be increased by subsidizing it. Two features of EU climate policy affect the practical implementation of such a policy. The first is the reference level, which affects policy design. The second is the cap, which may affect countries' incentives to adopt policies to promote carbon storage.

The application of reference levels means that countries can only account additional net removals generated by their forests. Thus, if a national regulator wishes to implement a national subsidy system to promote carbon storage, it too will be inclined to apply the additionality principle to the payments. Little is gained by paying for benefits that (i) do not contribute to towards the national reduction target, and (ii) would be obtained anyway, even without compensation. Thus, the subject matter of **Article III** is highly relevant in the context of the current EU regulation.

The caps limit the countries' potential to utilize forest sinks to mitigate climate change. If a country's forests generate net removals that exceed the cap, only removals up to the cap will be accounted as contributions towards the country's zero-emission target. Thus, if the cap is small relative to the potential removals that could be obtained by subsidizing carbon storage, it may de-incentivize the implementation of such a policy. There is no incentive to subsidize carbon storage if it does not contribute towards the country's target but, still increases climate policy costs.²⁷

The caps are determined relative to each country's total base-year emissions which largely depend on population size. Large (i.e. populous) countries have larger base-year emissions than small countries and, therefore, also larger caps than small countries. Hence, large countries (e.g. France, Germany, Italy, Poland, and Spain) can utilize their forests for climate change mitigation to a greater extent than small ones (e.g. Finland and Sweden), despite these small countries' large potential to generate large additional removals.

²⁶ Here, the word use ‘sink’ is used in its scientific meaning. This means that in absolute terms the forests remove more carbon from the atmosphere than they emit, even if the country's net emissions exceed the LULUCF reference level. Most EU member states' forests are carbon sinks.

²⁷ Unless a country voluntarily wants to implement a climate policy that is stricter than what is required by the EU.

If the cap is not binding,²⁸ emissions from wood-burning are fully accounted and, hence, a country's incentives to regulate wood-energy emissions remain intact. This is because all biomass that is removed from the forest is accounted as if it were oxidized immediately. Thus, there is no need to "double-count" the emissions from wood-burning. The situation is different if the cap is binding (i.e. if a country's net removals in forests exceed the cap). In this case, removing additional wood from the forest does not reduce the country's accounted net removals that contribute towards the emission target. Yet, wood burning is still treated as emission free. As harvesting and burning wood for energy does not show up in the accounts, the country's incentives to regulate these emissions are eroded. Thus, countries with non-binding caps are more likely to consider the taxation of bioenergy, than countries with binding caps. A binding cap may unfoundedly favor the energy use of wood.

EU policy regulates emissions in three sectors: the ETS sector, the ESR sector and the LULUCF sector. The ESR sector and the LULUCF sector have national reduction targets, whereas the ETS sector has an over-all cap at the EU level. A plausible objective for domestic regulators is to meet the national ESR and LULUCF sector targets cost-effectively. This means reducing emissions wherever it is least expensive. However, as the transfer of the mitigation burden between sectors and countries is limited by the restricting the use of flexibilities, it may not be possible to utilize land use sector mitigation measures to compensate for emissions in other sectors, where reductions are more expensive. This may lead to the under-utilization of the land use sector in climate change mitigation.

In addition to carbon, the EU climate policy also takes into account other greenhouse gasses. The contributions of other gasses are converted to carbon equivalents in the accounting using their Global Warming Potentials. The SCF methodology outlined in **Article IV** provides an alternative way to make such comparisons, based on damage rather than mere physical effects. Moreover, the SCF method also enables including forcing mechanisms that are currently not included in EU policy. In terms of land use, one important omission is surface albedo, which is of special interest in the boreal region with its seasonal snow-cover (Betts, 2000). Recently, the optimization (e.g. Thompson et al. 2009, Lutz and Howarth 2014) and optimal regulation (Rautiainen et al. 2018) of forest management for timber carbon and albedo have received attention in economic literature.

CONCLUSIONS

The land use sector can play an important role in global climate change mitigation efforts. The four articles in this thesis contribute to our understanding of how the sector can be optimally regulated for that end.

Optimal carbon storage can be attained by subsidizing carbon removal (into vegetation) and taxing emissions from soils, land use conversions and biomass utilization. One way to do that is outlined in **Article I**. Ideally, such a policy should be implemented globally to prevent leakage. However, as global implementation may be difficult (at least in the near future), countries considering land use sector carbon policies may also need to also consider complementary border tax adjustments to reduce leakage. This is a topic for further research.

The Effective Emission Factor outlined in **Article II** enables (1) comparing the harmfulness of CO₂ emissions from fossil fuel and biomass combustion (when logging residues are used for bioenergy), and (2) organizing the taxation of these emissions

²⁸ Here, we consider a cap to be binding, if the country's net removal equal or exceed the cap. I.e. by increasing actual removals, the country cannot increase the amount of removals that are *accounted* towards its emission reduction target.

consistently with one another. When fossil fuels are combusted, carbon is emitted into the atmosphere. This carbon would not be released, if the fuels were not utilized. Carbon is also emitted when logging residues are combusted. However, even if the residues are not burned, much of the carbon contained in them will be gradually emitted as the residues decompose. The harmfulness of fossil carbon emissions can be assessed by pricing them according to their social cost. The harmfulness of bioenergy emissions depends on how strongly we prefer the slow release of carbon to an immediate one. Two factors affect this judgment: (1) our time preference and (2) our expectations regarding the social cost of future carbon emissions. However, two general conclusions hold despite the variation in views regarding discounting and expectations regarding the future development of the SCC. Firstly, in terms of climatic impacts, bioenergy of Nordic forest residues is less harmful than peat and coal. Secondly, small residues, such as small branches and foliage, are also less harmful than natural gas, which is the cleanest fossil alternative. In this respect, the results for large residues, such as large branches and stumps, are more sensitive to the assumptions.

Increasing carbon storage in forests is one way to mitigate climate change. Recent studies suggest that in relatively forested regions, such as the Nordic countries, carbon storage in forests could be notably increased by subsidizing it (Sjølie et al. 2013, Pohjola et al. 2018). However, as we show in **Article III**, such subsidies can cause a high regulatory cost burden, and attempting to avoid this problem by paying for only additional carbon storage can lead to a suboptimal outcome. We show that in the stand-level context, in which land use is fixed, the additionality principle could be applied without distorting the optimal rotation by applying site productivity taxation to forestry. However, we show that a similar approach does not work as well at the market-level, as it distorts the land allocation as well as the optimal rotation. Such distortions can be avoided by eliminating excessive subsidies by general land taxation (aimed at agriculture as well as forestry) instead of taxing forestry only. Nevertheless, if this is not possible, complementing subsidies for carbon storage with corrective site productivity taxation may still be preferable to alternative second-best policies.

In addition to CO₂, various forcing agents and mechanisms also contribute to radiative forcing. To enable the inclusion of all forcing agents in a climate policy that is based on pricing externalities according to their social cost, or to be able to include the social value of these externalities in cost-benefit analysis, other forcing agents must be valued consistently in the same way as CO₂. That is, radiative forcing of the same magnitude, occurring at the same time, must have the same price irrespective of which forcing agent causes it. In **Article IV**, we show that there is a fundamental price, the Social Cost of Forcing (SCF), which can be used to price forcing agents of any kind, as long as their temporal radiative forcing profiles are known.

This thesis contributes to our understanding of optimal land use sector climate policy design. Nevertheless, the implementation of well-functioning and meaningful climate policies also requires tackling a number of practical challenges. Climate policy is decided democratically. Thus, the policies that are implemented in practice are not necessarily welfare-maximizing or efficient, but instead, political compromises between the miscellaneous objectives of various political groups. Also, the pre-existing policy environment affects the possibility of implementing new policies, and must therefore be taken into account in their design. For example, in EU countries, new land use sector climate policies must be compatible with EU's ESR and LULUCF regulations. At present these regulations may limit the potential to implement certain cost-effective mitigation policies in the land use sector. However, an improved understanding of optimal policy design can help improve the regulations when they are re-evaluated.

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