Department of Economics

Essays in Environmental and Resource Economics

Jussi Lintunen

Aalto University

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Essays in Environmental and Resource Economics

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Abstract

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Abstract

This thesis consists of four essays on environmental and resource economics. The two first essays analyze the climate policy, the third one focuses on timber markets and the fourth combines a climate policy with timber markets.

The first essay examines business cycle fluctuations of an optimal emission price with a macroeconomic general equilibrium model. The analysis shows that emission price tends to be procyclical as its fluctuations are connected to the changes in the marginal utility of consumption. A quantitative assessment shows that the optimal fluctuation of emissions depends on the production technology in the energy sector.

The second essay examines the optimal allocation of new allowances in an emissions allowance market, when banking of allowances for later use is allowed. The allocation decision faces a time-consistency problem because the banking decision is forward looking. To tackle this issue we examine a Markov solution of the planning problem. The quantitative assessment with a climate policy shows that the regulator prevents the accumulation of the banked allowances, and tries to maintain a stable allowance price level.

The third essay constructs a competitive equilibrium timber supply from the binary final felling decisions of individual forest owners, when the forests are age-structured and timber demand varies randomly. The model gives a stand-level interpretation for a generic market-level model and an empirically testable structure for future studies. The numerical results suggest that the insights drawn from the preceding stand-level analysis may be unwarranted in a competitive equilibrium.

The fourth essay examines an optimal climate policy in the forest and energy sectors. In the essay we combine an age-structured forest, the carbon cycle, and the different ways of using timber in a single model and derive an optimal climate policy for this system. We analyze two different carbon accounting schemes and show that a climate policy can be based on either of these. The numerical results suggest that carbon sequestration into forest biomass has priority in the mitigation of atmospheric carbon concentration.

Keywords climate policy, timber markets, business cycles

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Tiivistelmä

Tämä väitöskirja koostuu neljästä esseestä, jotka kuuluvat ympäristö- ja luonnonvarataloustieteen tutkimusalaan. Kahdessa ensimmäisessä esseessä keskitytään ilmastopolitiikan analyysiin, kolmannessa puumarkkinoihin ja neljännessä yhdistetään ilmastopolitiikka puumarkkinoihin.

Ensimmäisessä esseessä tarkastellaan makrotaloudellisella kokonaistasapainomallilla optimaalisen päästömaksun heilahtelua suhdannevaihteluiden mukana. Analyyttinen tarkastelu osoittaa, että optimaalisen päästömaksun vaihtelu on lähtökohtaisesti myötäsyklistä, koska se kytkeytyy kulutuksen rajahyödyn vaihteluihin. Numeerinen tarkastelu osoittaa, että päästöjen optimaalinen vaihtelu riippuu päästöjä tuottavasta tuotantoteknologiasta.

Toisessa esseessä tarkastellaan päästökauppajärjestelmän päästöoikeuksien määrän hallintaa, kun päästöoikeuksien tallettaminen myöhempää käyttöä varten on sallittua. Eteenpäin katsova talletuspäätös johtaa päästöoikeuksien määrän hallinnan aikaepäjohdonmukaisuusongelmaan. Tämän vuoksi tarkastelemme suunnittelijan ongelman Markov-tasapainoratkaisua. Numeerisesta ilmastopolitiikkasovelluksesta havaitaan, että suunnittelijan kannattaa estää päästöoikeuksien varaston kasvu ja pyrkiä pitämään päästöoikeuksien hintataso vakaana.

Kolmas essee konstruoi kilpailullisen tasapainon puuntarjontakuvauksen yksittäisten metsänomistajien binäärisistä päätehakkuupäätöksistä, kun metsillä on ikärakenne ja puun kysyntä vaihtelee satunnaisesti. Malli antaa metsikkötason tulkinnan usein käytetylle markkinatason mallille ja empiirisesti testattavan rakenteen tulevia tarkasteluja varten. Numeeriset tulokset antavat ymmärtää, että aiemmista metsikkötason mallinnuksista saatu ymmärrys ei välttämättä päde kilpailullisessa tasapainossa.

Neljäs essee tarkastelee optimaalista ilmastopolitiikkaa metsä- ja energiasektorilla. Esseessä yhdistetään ikärakenteinen metsä, hiilen kierto sekä puun eri käyttötavat yhteen malliin ja johdetaan systeemille optimaalinen ilmasto-ohjaus. Tarkastelu tehdään kahdella erilaisella hiilen kirjanpitojärjestelmällä ja osoitetaan, että ohjaus voidaan perustaa kumpaan tahansa näistä. Numeeristen tulosten perusteella hiilen varastointi metsiin näyttäisi olevan ensisijainen metsien käyttötapa ilmakehän hiilipitoisuuden hillinnässä.

Avainsanat ilmastopolitiikka, puumarkkinat, suhdannevaihtelut

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Helsinki, December 2018
Jussi Lintunen

Contents

List of Essays

This thesis consists of an introduction and the following essays.

I "Optimal emission prices over the business cycles" joint with Lauri Vilmi
Unpublished manuscript.

II "Business cycles and emission trading with banking" joint with Olli-Pekka Kuusela
European Economic Review, 101, 397–417. doi:10.1016/j.euroecorev.2017.10.015

III "Competitive harvest in age-structured forests"
Unpublished manuscript.

IV "On the economics of forests and climate change: Deriving optimal policies" joint with Jussi Uusivuori
Journal of Forest Economics, 24, 130–156. doi:10.1016/j.jfe.2016.05.001

Introduction

1 Background

To mitigate the climate change, a wide variety of actions is required. The anthropogenic carbon emissions, in the form of CO_2, are the main driver of the greenhouse effect that warms the Earth. Hence, the primary mitigation method is the reduction of the level of anthropogenic CO_2-emissions. Since the impacts of CO_2-emissions are an externality, the reduction of emissions requires regulation. Assuming that we know the marginal welfare loss of a marginal unit of CO_2-emissions in monetary terms, that is, the social cost of carbon (SCC), we could set a Pigouvian tax for the emissions (Pigou, 1920). In theory, the Pigouvian tax on CO_2-emissions would reduce the emissions to the socially optimal level, if its level is equal to the SCC. Another way to introduce a price for the CO_2-emissions, is to require an emission allowance to be submitted for each unit of CO_2-emission. If the total number of allowances allocated to the market is sufficiently small, the scarcity will generate a price on these allowances. If the trading of allowances is allowed, there will be a single emissions price for the regulated sector. Given that the allowance allocation is optimal, the allowance price will be equal to the SCC.

Another way to mitigate climate change is to sequester atmospheric carbon into living biomass. For example, the photosynthesis of the trees fixes CO_2 into the biomass of the tree. While the carbon remains in a tree it is not in the atmosphere strengthening the greenhouse effect. Again, the carbon capture by trees is an externality. Hence, regulation is needed for the carbon sequestration to reach its socially optimal level.

This thesis examines both the emission reduction policies that introduce an emissions price and the polices that incentivize the sequestration of carbon into forest biomass. There are specific questions the thesis seeks to answer: First, how should the SCC fluctuate over the business cycles? Second, how should the allocation of emission allowances fluctuate when their demand fluctuates randomly and the unused allowances can be banked for the future use? Third, how are the forest owners' decisions aggregated into timber supply in a rational expectations equilibrium? Fourth, what kind of portfolio of taxes and subsidies is needed in order to implement consistent climate policy on forest carbon?

Although the four questions seem to lack common elements, there are links between the themes and models. The two first questions are strongly interrelated as they both examine emission pricing when the economy is fluctuating randomly. However, the SCC question is examined in a macroeconomic context whereas the emission trading model extends the classical Weitzman (1974) setup. The two latter questions are focusing on timber markets when the forest resource has age-structure. The forest carbon question is naturally linked to the other two climate policy questions. Interestingly, both the emission trading and the timber supply models build on ideas of competitive storage (Deaton and Laroque, 1992). Thus, seemingly unrelated topics and models have linking attributes.

The rest of the introductory chapter is structured as follows. Section 2 presents the underlying theory for economic analysis of climate change and summarizes Essays I and II. Section 3 presents the forest economic theory behind Essays III and IV and summarizes these essays.

2 Essays I and II

2.1 A prototype climate model

In order to consistently analyze climate policies one needs to have a model that is sufficiently realistic description of the climate system. To this end one needs to adapt scientific literature on the climate system to allow for economic analysis of the policy measures. The starting point is a model for the global mean temperature deviation, T_t, which measures the level of anthropogenic climate warming. Given this definition, without human interference, in a steady-state $T_t = 0$. The development of temperature is driven by anthropogenic radiative forcing, F_t, which measures the strength of the greenhouse effect. High radiative forcing leads to high temperatures. Human actions that increase warming increase the radiative forcing. The relation between temperature change and radiative forcing can be approximated by a difference equation

$$T_{t+1} = T_t + \tau_T^{-1} \left(\alpha_F F_t - T_t \right). \tag{1}$$

In the equation, parameter α_F denotes the equilibrium sensitivity of temperature to a permanent change in radiative forcing. The second parameter τ_T is the relaxation time of the temperature giving a time-scale for temperature changes. It is clear that $F_t = 0$ leads to $T_t = 0$ asymptotically.

There are several contributors to the radiative forcing such as atmospheric carbon, methane, other greenhouse gases as well as other kinds of forcing agents such as the surface albedo of the Earth. This presentation concentrates on atmospheric carbon, the stock of which is denoted by S_t. Let's denote the radiative forcing as a sum of the effects of other contributing factors, F_t^O, and carbon, F_t^C,

$$F_t = F_t^O + F_t^C, \tag{2}$$

where (e.g. Shine et al., 1990, and references therein)

$$F_t^C := \frac{\alpha_S}{\log 2} \log \frac{S_{pre} + S_t}{S_{pre}}. \tag{3}$$

Here, α_S denotes the magnitude of radiative forcing by carbon. It is calibrated to the level corresponding to the doubling of atmospheric carbon stock compared to the pre-industrial level, S_{pre}. The product of the two sensitivity parameters α_F and α_S in equations (1) and (3), respectively, is often called as the climate sensitivity. The climate sensitivity denotes the equilibrium temperature increase from doubling of atmospheric carbon stock.

The regulation of CO_2-emissions aims at restricting the increase of atmospheric carbon stock. From the modeling point of view, this boils down to specifying how anthropogenic carbon emissions, E_t, contribute to the atmospheric carbon stock, S_t, and how does this stock develop over time. The oceans and biomass act as a carbons sinks that absorb excess carbon from the atmosphere. These processes operate in several time-scales (e.g. Joos et al., 2013) but here I present the simplest case where there is only one decay mode. With this setup, the development of the atmospheric carbon stock is determined by equation

$$S_t = (1 - \tau_S^{-1}) S_{t-1} + E_t, \tag{4}$$

where τ_S denotes the time-scale of atmospheric carbon decay.

Both specifications, (3) and (4), are simplifications of scientific estimates (e.g. Boucher and Reddy, 2008, Joos et al., 2013), which themselves are simplifications of the real climate processes. However, a simple climate system of equations (3) and (4) can be used to fix ideas and can often be sufficient for economic analysis.

In order to perform cost-benefit analysis, an estimate of the damages is also needed. To this end, it is natural to assume that the damages are associated with the global temperature deviation T_t. The damages can be caused through productivity losses (e.g Nordhaus, 1993) or direct welfare losses (e.g Weitzman, 2010). In any case, due to equation (1), a marginal increase in radiative forcing will cause a lasting increase in marginal damages. The net present value of these marginal damages defines a social cost of radiative forcing (SCF) (Rautiainen and Lintunen, 2017). Since the emitted carbon has a lasting effect on radiative forcing (equations (3) and (4)), the social cost of carbon (SCC) is a net present value of these forcing increments, where forcing is priced by the SCF (Rautiainen and Lintunen, 2017). Temperature based productivity loss damages are used in Essay I.

In sectoral partial equilibrium models other, even simpler, damage formulations may suffice. One step of complexity is dropped if the damages are based on atmospheric carbon stock S_t. In that case marginal damages, say $D_t'(S_t)$, aggregates the future welfare losses from the radiative forcing increment caused by the small atmospheric carbon increment. In monetary terms this is a valid measure for climate damages, but the use of S_t in productivity loss proxy may be unwarranted (ch. Heutel, 2012).

The simplest setup omits the stock variables and defines damages through carbon emissions only. In this flow-variable setup, marginal damages, say $D_t'(E_t)$, denote the value of the SCC. If the sector is small enough and the time horizon of the analysis short, it is plausible to assume that the SCC does not depend on the emissions of that sector, that is, marginal damages are constant. In that case, $D_t(E_t) = SCC_t E_t$. Formulation, $D(S_t)$, was used in Essay IV, whereas linear $D(E_t)$ formulation was deemed sufficient in Essay II (e.g Newell and Pizer, 2008).

2.2 Carbon regulation

In the first-best optimal world, all the CO_2 flows, both emissions and removals, should be priced with the SCC. From the view point of a firm that emits CO_2, the input use problem would then be

$$\max_{q_t} R_t(q_t) - C_t(q_t) - p_t^c \varepsilon q_t, \tag{5}$$

where q_t denotes the use of polluting input and functions R_t and C_t are the revenues and costs, respectively. Parameter ε is the emission factor associated with input use and p_t^c is the CO_2 price. If $p_t^c = SCC_t$, the firm's input use and, thus, emissions are at socially optimal level. This can be arranged, for example, by a Pigouvian emissions tax τ_t and setting $\tau_t = SCC_t$ (Pigou, 1920).

Instead of using a direct price regulation, the emission control can be arranged using quantity regulation (Dales, 1968, Montgomery, 1972). With quantity regulation the regulator sets a cap for the total amount of emissions, Q_t. The cap specifies the number of emission allowances that the regulated firms are required to surrender to match their emissions. If the cap is low enough, the scarcity of emission allowances generates a price to the emissions. In addition, if the emission allowances are tradable between firms, there will be one emissions price for the regulated sector. If the emission cap is optimally set, the resulting emission price is equal to the SCC, i.e., $p_t^c = SCC_t$.

While the two approaches are equal in world of certainty, their expected performance differs under uncertainty. In his classical paper, Weitzman (1974) showed that under uncertainty, if the marginal environmental damages have greater slope than the marginal economic benefits in absolute terms, the quantity regulation is more efficient. This follows directly from the fact that firms do not observe marginal damages but either the emissions price or the emissions cap imitates the marginal damages. As a result, when the marginal damages are flat, as is the case with climate change, the fixed price mimics the marginal damages better and the emissions tax is superior to the emissions cap. Analogously with steep marginal damages, the quantity regulation is preferred.

In the Weitzman's setup the uncertainty was introduced through random levels of marginal damages and benefits. The randomness of the two functions was uncorrelated in which case the randomness of marginal environmental damage (or marginal abatement benefit in Weitzman model) has no effect on relative performance of the two regulations. However, Stavins (1996) showed that if the two "shocks" are correlated, the simple rule for relative performance is changed. For example, if both the marginal benefits and damages tend to be low (and high) at the same time, the optimal quantity changes relatively less but the optimal price may fluctuate more. Thus, positive correlation between marginal benefits and damages improves the quantity regulation relative to the price regulation.

The quantity policy can be augmented, for example, by introducing collars for the allowance price (e.g. Roberts and Spence, 1976, Weitzman, 1978), which turns the regulation into a price-quantity hybrid. In general, this kind of hybrid can be welfare improving compared to simple price and quantity regulations. The quantity regulation can also allow inter-temporal trade of the allowances, that is, banking of allowances for later use and/or borrowing of allowances from future periods (e.g. Rubin, 1996). The inter-temporal trade allows firms to even out costs between periods, which can reduce policy costs. However, this kind of abatement cost minimization by the firms may distort the outcome from the social optimum (Kling and Rubin, 1997).

Naturally, the implementation of both the price and quantity regulations faces many practical challenges, the most fundamental being the assessment of the level of the SCC. Due to the extensive economic effects of the climate externality, the analysis of the optimal regulation requires macroeconomic modeling that is augmented with a representation of the climate system. Pioneering examples of these kinds of integrated assessment models are DICE (Nordhaus, 1993) and FUND (Tol, 1997). After the famous *Stern review* (e.g. Stern, 2007, Nordhaus, 2008), the integrated assessment models have also been developed towards analytical direction (Golosov et al., 2014, Gerlagh and Liski, 2017, 2018).

These integrated assessment models that are used for determining the level of the SCC focus on long-term phenomena. However, there has also been interest on analyzing the effects of business cycles on the performance of climate policies. For example, the European union emission trading system, EU ETS, has witnessed drastic allowance price changes during its existence, which has culminated in a decline during 2008–2013. This price drop may have been, at least partly, driven by the persistent economic downturn in 2009: Inflexible allowance allocation rule and inflow of allowances from JI and CDM mechanisms under lower demand caused by economic downturn lead to allowance build-up. The build-up was huge, which resulted in decrease in expected and, therefore, current allowance prices. This rises a question: how much, if at all, should the optimal carbon price fluctuate over the business cycles?

The first who studied the business cycle properties of climate policies with a real business cycle (RBC) model were Fischer and Springborn (2011). Heutel (2012) provided an alternative view in which a planning solution that took into account the climate externality was introduced. The decentralization of the planning model suggested that the optimal carbon price should be procyclical. However, Heutel (2012) does not provide a definite answer on what drives the optimal carbon price fluctuations and what determines their magnitude. Essay I provides insight on why the SCC tends to be procyclical. In addition, the essay compares the optimal carbon pricing with fixed tax and quantity regulations in parallel to original prices vs. quantities literature.

With quantity regulation the problem is to find an optimal emissions cap. The problem can be tackled from the basic principles of cost-benefit-analysis. If the emissions cap is set under uncertainty of the economic benefits (or in other terms, abatement costs) the optimality can only be obtained in expectations. Essay II examines a Markov policy for optimal emissions cap when the banking of allowances is allowed but the borrowing is not. Using the insights of competitive storage literature (Deaton and Laroque, 1992, 1996), the essay explicitly shows that allowing banking but not borrowing leads to a regulation where the allowance price has an endogenous price floor. Hence, the banking of allowances turns a quantity regulation into a price-quantity hybrid. This price floor has implications on how the emissions cap should be set.

2.3 Summary of Essay I. Optimal emission prices over the business cycles

Essay I builds a real business cycle (RBC) model with an integrated climate system module. The climate system module approximates the scientific literature on the dynamics of the global mean temperature and atmospheric carbon stock (Boucher and Reddy, 2008, Joos et al., 2013). The RBC module contains two types of capital stocks. The first is used for final good production and the second is utilized in the generation of energy services. The energy services can also be produces with an input that emits carbon into atmosphere. The use of energy sector capital does not emit carbon. The level of energy services is a constant elasticity of substitution (CES) aggregate of the energy sector capital and the input use. The value of the elasticity substitution summarizes the production technologies of the energy sector: A low elasticity implies that the capital is mostly connected to the input use, such as fossil fuel power plants, whereas a high elasticity describes a situation where a larger share of the capital is independent of polluting input use, such as photovoltaics and wind turbines.

The modeling extends the previous work on climate policies under business cycles Heutel (e.g. 2012) in two aspects. First, we implement a more detailed description of the climate system. Specifically, we assume that carbon stock in the atmosphere induces increase in global mean temperature, which measures the environmental problem and causes economic damages. Hence, our model incorporates an additional level of dynamics, which introduces a time lag between the emissions and resulting economic damages. Second, instead of using implicit abatement technology, we directly model the polluting input use. In the model, emission reductions can only be made by reducing input use. The negative welfare effects of input use reduction are mitigated by increased use of energy capital, which provides energy services without emissions. Hence, the cost of abatement depends on the substitutability between input use and energy capital.

The essay analyzes the model and provides a formula for the optimal emission price, which in the case of climate change, is the social cost of carbon (SCC). The emission price formula is then used in analyzing the constituents of the SCC fluctuations. The essay shows that the main driver of the SCC fluctuations are the fluctuations in the marginal utility of consumption. This largely explains the procyclicality of the SCC and suggests that SCC fluctuations are relatively modest in magnitude. In addition, the essay compares the optimally adjusted carbon price with both the fixed emissions price and fixed emissions quantity regulations and show that, in general, the fixed tax performs relatively well compared to the optimal pricing and seems better than fixed quantity. This can be understood from the the static prices vs. quantities perspective (Weitzman, 1974) in which a fixed tax is preferred over a fixed cap regulation due to flat marginal benefits implied by the the climate system (Hoel and Karp, 2001, 2002, Newell and Pizer, 2003). However, the relative performance of fixed cap and fixed tax regulations is affected by the correlation between shocks of marginal benefit and marginal cost functions (Stavins, 1996). In the essay, a low elasticity of substitution in energy sector implies positive correlation between these shocks, which prefers fixed quantity regulation.

2.4 Summary of Essay II. Business cycles and emission trading with banking

The essay II examines the forward-looking Markov allocation rule of new emission allowances, when the regulator balances between the economic emission benefits and environmental emission damages, and the firms can bank excess allowances for later use. In the essay, the economic fluctuations are stochastic and the regulator has to set the allocation of new allowances before the economic shock is realized. However, before setting the cap for the next period, the regulator observes the amount of allowance in the bank. To keep the model as simple as possible, the essay omits the stock nature of the climate pollution, but instead apply flow damages with linear damage function (e.g. Newell and Pizer, 2008). The model features infinite time horizon and, therefore, the model setup can be seen as a dynamic extension of the seminal prices vs. quantities setup (Weitzman, 1974) and later two-period models (Yates and Cronshaw, 2001, Feng and Zhao, 2006).

The information structure allows the regulator to set the level of the emissions cap for the next period despite the amount of allowances in the bank. Since the marginal damages are constant, the regulator using a Markov policy aims at setting the expected allowance price level to a constant level too. A price target together with the ability to control the periodic emissions cap nullifies the expected price effects of the banked allowances. Thus, the model differs from the usual competitive storage setup, where the inventories decrease the price expectations (Deaton and Laroque, 1992, 1996). This changes the role of banking into a insurance mechanism: The banking motives prevent low allowance prices when the allowance demand is low and, therefore, the regulator can increase the emissions cap to prevent excessively high allowance prices when the demand is very high.

The quantitative assessment with stylized EU ETS data showed that the Markov policy can rely heavily on banking. The modeled periodic cap was so high that only for a quarter of periods the cap is binding. However, the policy prevents the build-up of allowances by maintaining emissions cap that implies a constant expected emissions price. Thus, the cap is increased when the demand is expected to by high and vice versa. The resulting periodic allowance prices are independently and identically distributed. In addition, the price distribution has an atom, where with three quarters probability the allowance price is equal to the present value of the expected next period price. The quantitative assessment suggests that the welfare gains could be reasonable when contrasted with the actual EU ETS outcome during 2008–2013.

3 Essays III and IV

3.1 Forest economics: Stand level

In this thesis, I focus on the economics of planted forests when the forest owners follow principles of even-aged timber management. The basic problem of even-aged management is the choice of the optimal harvest age, i.e., the rotation. Naturally, the optimality depends on the forest owner objectives. Here, I assume that the forest owner maximizes the net present value of revenues minus regeneration costs. In the basic setup, examined already by Faustmann (1849), the revenues consist of mere timber harvest revenues. If the climate externality is internalized, the carbon flows of forest stands are priced by the social cost of carbon. The tree growth fixes carbon from the atmosphere and the harvests (and subsequent use of timber) ultimately releases the carbon back into atmosphere, which means that growth is connected to a sequestration subsidy and harvest to a emission tax. However, the forest carbon policy can equivalently be formulated as a “carbon rent” regulation (e.g. Sohngen and Mendelsohn, 2003, Lintunen et al., 2016), where the subsidies are based on the amount carbon stored in the forest stand. In addition to practical differences, the theoretical advantage of the carbon rent regulation is that it conforms with the usual monetary age-dependent *in situ*, or amenity, value model (Hartman, 1976). Thus, as an extension of the basic timber revenue setup, I will assume preferences with amenity values, which can be understood as stand-age-dependent carbon rent payments.

In the classic optimal rotation problem, all the parameters such as timber price, p, regeneration costs, c, interest rate, r, and the site productivity are time-invariant.[1] Since the calendar time does not affect the optimal forest management, the optimal rotation and the forestry based land value will be the same forever. It is practical to examine the bare land

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[1] Timber price denotes here stumpage price and, therefore, harvest costs can be omitted in the analysis. This is based on simplifying assumption that harvest costs are equal between age-classes.

value, that is, the land value before the stand is regenerated. I denote the bare land value as *the land expectations value*, LEV_a, where subscript a denotes the applied rotation age. In the discrete time Hartman setup, the LEV_a depends on rotation age a through equation

$$LEV_a = -c + \sum_{a'=0}^{a-1} \beta^{a'} A_{a'} + \beta^a p q_a + \beta^a LEV_a, \tag{6}$$

where $\beta = (1+r)^{-1}$ is the discount factor, q_a is the age-dependent per hectare volume of timber, and A_a are the age-dependent *in situ* values.[2] Thus, the land value consists of regeneration costs, sum of discounted *in situ* values, and discounted harvest revenue plus the value of the cleared land.

Equation (6) assumes that the land continues to be in forestry use after the first rotation. Since the model parameters do not change the bare land values before and after the rotation are equal. Thus, the bare land value can be written as

$$LEV_a = \frac{-c + \sum_{a'=0}^{a-1} \beta^{a'} A_{a'} + \beta^a p q_a}{1-\beta^a}. \tag{7}$$

This is the discrete time Hartman formula for land value when forests provide *in situ* values (Hartman, 1976). If these values do not exists, but $A_a = 0$, equation (7) reduces to the usual Faustmann's formula of forest land value (Faustmann, 1849).

Maximization of the land value as defined in (7) by finding the optimal rotation, a, is the standard approach of forest economics. The approach can be seen as a "planning" problem, where the forest owners decision making is abstracted away. In the planning problem the site specific growth properties dictate the optimal forest management under assumed fixed prices, costs and interest rate, even before the trees are planted. The fixed parameters restrict the feasibility of the model: If some of the fixed parameters is changing, the approach becomes unusable. Thus, the planning problem has only limited value when the aim is to study timber supply decisions of the forest owners in a timber market equilibrium.

An alternative to the planning view is a model where the forest owner's period-to-period harvest decision is central. In this alternative approach, the forest owner makes in each period the decision between (i) harvesting the forest stand and (ii) waiting. Both actions have value, denoted here by

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[2] The volume development depends on the productivity of the site. Here, it suffices that the volume grows with age, $q_a > q_{a-1}$, and the growth rate declines with age, $q_{a+1}/q_a < q_a/q_{a-1}$.

$v_{at}^{harvest}$ and v_{at}^{wait}, respectively, and the forest owner chooses the one which has the highest value. Hence, the forest owners' decision problem is

$$v_{at} = \max\{v_{at}^{wait},\, v_{at}^{harvest}\}, \tag{8}$$

for all $a > 0$ and t. The choice specific values are

$$v_{at}^{wait} = A_{at} + \beta \mathbb{E}_t v_{a+1,t+1}, \tag{9}$$

if the forest owner decides to wait and

$$v_{at}^{harvest} = p_t q_a + LEV_t, \tag{10}$$

if the forest owner harvests the forest stand. Assuming that the land remains in even-aged forestry after the clear cutting, the bare land value is

$$LEV_t = -c + v_{0t}, \tag{11}$$

where c is regeneration cost and v_{0t} the value of land after regeneration, that is, value of zero years old stand. Mathematically the problem is a (continuous) Markov decision problem, where current state and action determine the probability distribution of the future state. However, the model does not have to involve uncertainty, but the price changes can be deterministic.

The forest owners' decision can be characterized by a reservation price π_{at}, i.e., forest owner harvests if $p_t > \pi_{at}$. Given equations (8)–(11), the reservation price is

$$\pi_{at} = \frac{A_{at} + \beta \mathbb{E}_t v_{a+1,t+1} - LEV_t}{q_a}. \tag{12}$$

The higher the *in situ* value, A_{at}, and expected present value of unharvested stand, $\beta \mathbb{E}_t v_{a+1,t+1}$, the higher the reservation price. Analogously, high bare land value, LEV_t, and timber volume, q_a, lead to low reservation prices. The connection between the reservation price and the short-run timber supply is examined in Essay III.

In order to find a solution to the general problem (equations (8)–(11)) more structure is needed. This is done in Essay III with assumption $A_a = 0$. However, assuming constant parameters p, c, and β, the problem reduces to the discrete time Hartman model presented above. Because the procedure showing the equivalence of the two approaches provides insight on the underlying logic of Faustmann and Hartman models, I will next turn to that.

In the classic Faustmann and Hartman problems the timber price, the land expectations value, and the amenity value are time-invariant. Hence, waiting and harvest values do not depend on calendar time but only on age. For stands, that are and remain in wait-mode, using equation (9) and (11), we can formally write

$$v_a^{wait} = (LEV + c)\beta^{-a} - \sum_{s=1}^{a} \beta^{-s} A_{a-s}, \tag{13}$$

for all $a \geq 1$. In a static setup, the harvest value is simply time-invariant version of equation (10), i.e.,

$$v_a^{harvest} = pq_a + LEV. \tag{14}$$

Both the Faustmann and the Hartman problems aim at finding the harvest age a^* which maximizes the bare land value. This maximal value is here denoted by LEV. The only difference between the two models is that in the Faustmann problem, there are no amenity values, that is, $A_a = 0$ for all a. Hence, the value of forest stand in wait-mode is different in the two model framworks while the harvest value remains formally the same.

Given that there is a unique finite optimal harvest age $a^* < \infty$, the optimal solution is such that the forest stand remains is wait-mode until the optimal harvest age is reached and stand value is given by the harvest value,

$$v_{a^*} = v_{a^*}^{harvest}. \tag{15}$$

By equation (9), $v_{a^*-1}^{wait} = A_{a^*-1} + \beta v_{a^*}$, which with equations (13), (14), and (15) leads to equation

$$pq_{a^*} + LEV = (LEV + c)\beta^{-a^*} - \sum_{a=1}^{a^*} \beta^{-a} A_{a^*-a}. \tag{16}$$

This can be rewritten as

$$LEV = \frac{-c + \sum_{a=0}^{a^*-1} \beta^a A_a + \beta^{a^*} pq_{a^*}}{1 - \beta^{a^*}}, \tag{17}$$

which is the Faustmann/Hartman formula for the bare land value (7).

The solutions to the Faustmann and Hartman problems are illustrated graphically in left and right panels of Figure 1, respectively.[3] Solid lines

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[3] In the illustration, $q_a = 746(1 - 8.56^{-a/87.1})^{3.52}$ m^3/ha, which approximates the timber volume obtained from MOTTI-simulation (Hynynen et al., 2002, Salminen et al., 2005) for a spruce stand in fertile growth conditions at Muhos, Finland. Timber price $p = 35$€/m^3, regeneration costs $c = 1000$€/ha and annual interest rate $r = 3\%$. In the Hartman case the *in situ* values are defined as carbon rent, that is, $A_a = rp_{CO2}\rho\gamma(q_a)$, where emission price $p_{CO2} = 20$€/t$_{CO2}$, carbon to CO$_2$-multiplier $\rho = 44/12$, and timber volume to biomass carbon -function $\gamma(q_a)$ is based on scientific literature (Nurmi et al., 1997, Lehtonen et al., 2004).

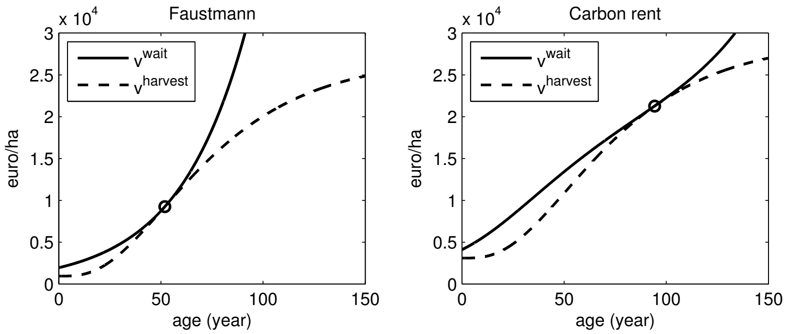

Figure 1. The effect of an *in situ* value, such as carbon rent, on the optimal rotation and bare land value. The circle presents point (a^*, v_{a^*}) in the two cases. Faustmann case: $a^* = 52$ yr and $LEV = 950$ €/ha. Carbon rent case: $a^* = 94$ yr and $LEV = 3100$ €/ha. The shape of waiting value is changed by the carbon subsidy. Instead, the harvest value $v^{harvest}$ is only shifted upwards by the amount $\Delta LEV = 2150$ €/ha.

present the value of the stand in wait-mode, v_a^{wait}, (equation (13)) and the broken lines depict the harvest value of the stand, $v_a^{harvest}$, which is the sum of current harvest value of timber and the optimal bare land value, LEV (see equation (14)). The wait value is the value of stand during the growth cycle and is above the harvest value until harvesting is optimal. In the Faustmann setup, the stand value sustains geometric growth, whereas in the Hartman setup the age-dependent amenity values affect the value growth. Optimal harvest age is the one where the two values tangent. This is shown by circle in Figure 1. Positive amenity values increase the value of waiting which increases the land value and the optimal harvest age.

3.2 Forest economics: Market level

In order to analyze the timber markets, the stand-level approach needs to be expanded in two critical aspects. First, one needs to specify the demand for timber that is satisfied by the supply. Second, one needs to extend the analysis to cover an area of land, which is used for supplying the timber. In this presentation, it suffices to define a inverse demand function, $P_D(h_t)$, which is a time-invariant decreasing function of harvested timber h_t. Essay III extends the situation to the case, where demand is shifted by stationary random shocks. More structure is needed for describing the forest resources of the analyzed land area.

The analysis here focuses on a fixed land area of equal timber productivity, that is, the age-dependent per hectare volume is given by the same parameters q_a in every parcel of land. The forest stands are even-aged, that is, all the trees of a forest stand belong to a same cohort. Under these assumption the state of the forest resources can be described by the age-structure of forest land. The age-structure is described by the age-class distribution (ACD). The ACD tells how the forest land is allocated between different age-classes of even-aged forest stands. I denote the ACD by $\boldsymbol{x}_t = (x_{1t}, x_{2t}, \ldots)$, where x_{at} denotes the hectares allocated to age-class a in period t.

If the forest stands are not harvested they age and grow in volume, and if the trees are harvested the harvested area is regenerated and contains youngest age-class timber in the next period. Given the share of harvested land in each age-class, $\theta_{at} \in [0, 1]$, this corresponds to the following dynamic relation between ACD now, $\boldsymbol{x}_t$, and in the next period, $\boldsymbol{x}_{t+1}$,

$$x_{1,t+1} = \sum_a x_{at}\theta_{at}, \tag{18}$$

$$x_{a+1,t+1} = (1 - \theta_{at})x_{at}, \quad \text{for all } a. \tag{19}$$

Note that total forest area $\sum_a x_{at}$ remains constant over time.

Naturally, the harvest shares also affect the amount of timber harvested. Namely, timber supply, h_t, is based on harvested areas of each age-class, i.e.,

$$h_t = \sum_a q_a x_{at}\theta_{at}, \tag{20}$$

where $x_{at}\theta_{at}$ indicates the harvested area in hectares and q_a the timber yield per hectare. Since timber volume grows with age, i.e., $q_a > q_{a-1}$, for all $a \in \{1, \ldots, A\}$, the timber supply potential is dictated by the ACD. If there are lots of hectares with old forests with great timber volume, the amount of harvestable timber is greater than if the ACD consists mostly of young stands with small trees.

One special case of age-class distribution, *a normal forest*, proves to be important. The ACD is a normal forest with rotation A, if the total land area, say X, is divided evenly between A age-classes, that is, $x_{at} = X/A$ if $a \leq A$, and $x_{at} = 0$ if $a > A$. To maintain such a *normal forest* over time, all the stands are clear-cut at age $a = A$, that is, $\theta_{At} = 1$ and $\theta_{at} = 0$, if $a \neq A$. If the normal forest is maintained, the harvest yield is constant over time. This kind of ACD configuration is also called as fully regulated forest or a synchronized ACD. The importance of normal forest configuration becomes apparent later.

The competitive equilibrium of a partial equilibrium model can be found by maximization of the net surplus (e.g. Mas-Colell et al., 1995). The net surplus is the sum of the consumer surplus and the producer surplus. Unlike in a standard textbook approach, in the analysis of timber markets, a dynamic setup is needed and the objective function of a planning model is the net present value of the periodic net surplus streams. Given a sequence of harvest share vectors $\boldsymbol{\Theta} = \{\boldsymbol{\theta}_t\}_{t=0}^{\infty}$ and initial ACD, $\boldsymbol{x}_0$, the objective function can be written as

$$J(\boldsymbol{\Theta}, \boldsymbol{x}_0) = \sum_{t=0}^{\infty} \beta^t \left\{ \int_0^{h_t} [P_D(h) - P_D(h_t)]dh + [P_D(h_t)h_t - c\sum_a \theta_{at} x_{at}] \right\} \tag{21}$$

$$= \sum_{t=0}^{\infty} \beta^t \left\{ \int_0^{h_t} P_D(h)dh - c\sum_a \theta_{at} x_{at} \right\}, \tag{22}$$

where the harvests, h_t, are given by equation (20). In addition, the development of the ACD is given by equations (18) and (19). Early variants of this setup has been formulated e.g. by Berck (1976), Lyon and Sedjo (1983), Mitra and Wan (1985).

Unlike in a typical, e.g., static, surplus maximization setups, surplus in equation (22) does not have a supply function, which could be based on explicit marginal costs. The only explicit costs are regeneration costs. However, it is not optimal to harvest all stands which generate harvest revenue greater than the regeneration costs, i.e., $p_t q_a > c$. Instead the supply function is implicitly defined by the inter-temporal linkages created by the age-classes dynamics (18) and (19). Thus, the solution of the problem from an arbitrary initial state $\boldsymbol{x}_0$,

$$V(\boldsymbol{x}_0) = \max_{\{\boldsymbol{\theta}_t\}_{t=0}^{\infty}} J(\boldsymbol{\Theta}, \boldsymbol{x}_0), \tag{23}$$

subject to equations (18), (19), and (20), implies that an age-class is harvested only if

$$p_t q_a > c + \beta V_{x_{a+1}}(\boldsymbol{x}_{t+1}) - \beta V_{x_1}(\boldsymbol{x}_{t+1}). \tag{24}$$

Here, the subscripts of V denote the partial derivatives. Equation (24) suggests that while the harvest costs, c, have a role in the harvest decision, the future marginal land values contribute to the harvest decision and make the decision age-dependent.

The model has been extensively analyzed in a special case where regeneration costs are zero (Mitra and Wan, 1985, Wan, 1994, Salo and Tahvonen, 2002a,b, 2003, 2004). This research has focused on the long-run equilibrium allocation of the land into different forest age-classes. The outcome of the research is that if the inverse demand is decreasing in harvests, i.e., utility is concave, the ACD gravitates towards a normal forest with harvest age equal to the Faustmann optimal rotation. However, the convergence is not perfect but persistent equilibrium cycles remain around the normal forest configuration. The reason for this is that the cycle smoothing would require deviations from the Faustmann optimal rotation, which, in a discrete time setup, incur non-zero costs. Instead, the gains from deviations approach zero as the price differences are smoothed out. Hence, there is a limit beyond which the size-differences of age-classes do not vanish. However, if there is an additional land-use class, such as agriculture, and there are no land-use conversion costs, the equilibrium cycles vanish as the additional land-use class can be used for cost smoothing (Salo and Tahvonen, 2004).

The market-level surplus maximization model (equation (23)) and the binary optimal stopping model (equations (8)–(10) presented above) are conceptually rather different. For the market-level model to be empirically relevant, the two models should represent similar forest management. In order to examine the equivalence between the surplus maximization model and a competitive equilibrium a decentralization of the surplus maximization model is needed.

In market equilibrium, the timber prices and land expectations value typically vary in time and, therefore, the time-invariant setups of Faustmann and Hartman models become inoperative. While the static setup can be extended to cases, where timber value or timber price are stochastic, these models are not easily adjusted to describe the situation where timber price is determined endogenously. Instead, it is natural to build such a decentralized market equilibrium model from the starting point of equations (8)–(11), where the forest owners short-term decision making is explicitly described.

Essay III builds a decentralization of the surplus maximization model and shows the conditions under which the surplus maximization model corresponds to the competitive equilibrium where forest owners make binary clear-cutting decisions for individual forest stands. The result implies that the surplus maximization model is reasonable description for competitive timber markets.

While stand-level forest economic analysis of forest carbon has long tradition (e.g van Kooten et al., 1995) the market level analysis using relatively transparent Mitra and Wan (1985), Salo and Tahvonen (2002a) approach is a relatively new branch of literature.[4] Cunha-e Sá et al. (2013) were the first to introduce carbon flows into the surplus maximization setup discussed above. In essay IV we introduce a carbon policy on land use. In addition, we expand the demand segment of the model by allowing several timber uses, which are regulated by the climate policy based on their effect on atmospheric carbon stock.

3.3 Summary of Essay III. Competitive harvest in age-structured forests

The essay III examines the forest owners' decision of optimal harvest age, when the timber price is formed by the periodic market clearing and the timber demand is stochastic. The forest owners are assumed to be price takers and compete with other forest owners. As a result, from the forest owners' point of view the timber price follows a price process that is endogenous to the aggregate equilibrium harvest decisions of all the forest owners.

Formally, the forest owners' problem is the optimal stopping of an aging process, when timber prices fluctuate randomly. However, the random process driving the timber price fluctuations is not explicit and the forest owners need to formulate price expectations from the current state of the timber market, that is, realization of the stochastic demand shock and the age-structure of the whole forest. If the harvesting problem is presented as a planning problem, the present model is an extension of the model by Mitra and Wan (1985). The extension is two-fold: First, the timber demand, or the utility in Mitra and Wan (1985) setup, follows a stochastic process. Second, the regeneration of harvested forest stands incur a cost. While the second extension seems relatively minor, it has notable consequences by introducing price-dependence to the optimal rotation length.

The essay examines the forest owners optimal policy and constructs a decentralization for the planning problem. The decentralization provides an explicit timber market description for further empirical and policy analysis. In addition, it provides a forest owner perspective for, e.g., the equilibrium cycles, observed in the deterministic planning setup (Wan, 1994, Salo and Tahvonen, 2002a,b, 2003). The decentralization presents

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[4] Forest carbon has been included also in large numerical models (e.g. Sjølie et al., 2013, Pohjola et al., 2018), which focus more on realistic data than theoretical insights. The theoretical insights are better obtained using simpler model structures.

an exact stand-level interpretation of the Mitra and Wan (1985) model, and, therefore, conceptually unites the optimal rotation and the equilibrium land allocation strands of literature.

The model shows that the forest owners apply a reservation price strategy. However, in a market equilibrium setting, postponing harvests increases the current timber price and reduces the expected future price. This is analogous to the building up the inventories in the competitive storage literature (Deaton and Laroque, 1992). These equilibrium forces constrain the forest owners' ability to postpone the harvests, when a low demand shock is realized. Similarly advancing the harvests in younger age-classes decreases current and increases expected future timber price. Again the market equilibrium restricts the forest owners' ability to benefit from random shocks. As a result, the competitive market prevents the accumulation of excessive rents that is observed in stand-level analyzes (Gong and Löfgren, 2007, and references therein).

3.4 Summary of Essay IV. On the economics of forests and climate change: Deriving optimal policies

The essay IV examines the dual role of forests and timber on climate change mitigation. First, the forest can be used as a carbon storage. Second, the wood from forests can be used as a substitute for fossil fuels or other carbon intensive raw materials such as cement. At least in short-term, the two roles are in conflict, since carbon sequestration in the forests is reduced if timber harvests are increased for the substitute role (Schlamadinger and Marland, 1996, Marland and Schlamadinger, 1997). It is natural to ask, which of the two roles of forests should have a priority. In the real world, the choice has proven to be a difficult one. Not only is the choice complicated by the non-permanent carbon storage both in soil and wood products (Aalde et al., 2006), but the whole scientific basis of substitution benefits is under debate (e.g. Fargione et al., 2008, Searchinger et al., 2008, Melillo et al., 2009, Wise et al., 2009, Schlesinger et al., 2010, Lippke et al., 2010, Gunn et al., 2012, Miner et al., 2014). The essay gives an answer to this question.

A parallel question is how should we setup a climate policy to regulate the forest carbon flows? Tahvonen (1995) showed that the optimal climate policy should tax all emissions based on the amount of carbon released by the combustion. However, the real climate policies, such as EU ETS, treat wood fuels as emission free. This has contributed to the apparent confusion over correct treatment of wood based bioenergy (Schlesinger et al., 2010, Lippke et al., 2010). A suggested solution is the fixing of flawed carbon accounting conventions (Searchinger et al., 2009, Haberl et al., 2012). The essay clarifies the role of the accounting conventions and shows that climate policy can be based on any complete accounting convention.

The model presents an age-structured forest and a stylized representation of the economy. The economy consumes energy, fast and slow decaying wood products (HWP), and cement. All the categories act as substitutes for each other. The model tracks the carbon flows between atmosphere, forest, and HWPs as well as the carbon emission by fossil fuel and cement use. From the modeling point of view the setup extends the age-class model with possibility of land-use change (Salo and Tahvonen, 2004) by introducing carbon flows and a wide set of wood use options. In the quantitative assessment, the model was calibrated to stylized Finnish conditions and solved with a fixed level of the SCC.

The essay shows that the climate policy can regulate wood use related emissions either in the forest or when the wood used. The first approach corresponds to the accounting convention used by UNFCCC and IPCC, whereas the second approach follows the real physical carbon flows (cf. Tahvonen, 1995). In the market equilibrium, both policies lead to same behavior. Only difference is in the level of the timber price. The optimal policy subsidizes carbon sequestration in the forests and taxes all emissions. However, the harmfulness of harvest residue emissions is deemed lower than that of fossil fuels, since the harvest residues would gradually release their carbon into atmosphere even if not combusted.

The quantitative assessment suggests that carbon sequestration into forests has the priority. Hence, an implementation of a complete carbon regulation leads to initial reduction of timber harvests as the harvest ages are gradually postponed. The fossil fuel use reduction is compensated by the energy use of harvest residues. When the forest resources reach their new equilibrium rotations, the timber supply increases as the harvest age is closer to the maximum sustainable yields rotation. When this happens, the increased forest resources provide raw material for forest based bioeconomy, and with the given parametrization, even to energy generation.

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