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Effects of taxes and climate policy instruments on harvesting of managed forests and on tropical deforestation

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Academic Dissertation

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ABSTRACT

This dissertation examines the effects of taxes and policy instruments that aim to regulate climate services from forests. It consists of a summary section and four articles. Articles (**I**) and (**II**) examine the effects of taxes on management decisions in the context of managed boreal forests distinguished by forest-owners' amenity preferences and also their age. Articles (**III**) and (**IV**) examine the role of carbon-based policy instruments in the presence of taxes on land incomes in curbing tropical deforestation.

Article (**I**) reveals that the intensity of forest-owners' preferences for forest amenities affects the non-neutrality of forest taxes pertaining to forest harvesting. Therefore, the effects of taxes depend on this intensity. This highlights the importance of developing methods to measure forest-owners' amenity preferences quantitatively. Article (**II**) shows that the age of forest-owners governs their propensity to consume as opposed to leave bequests. Furthermore, it shown that the effects of capital income and inheritance taxes vary across different age-groups of forest-owners. Article (**III**) demonstrates that taxes on forestry and cash-crop incomes, *per se*, may be ineffective in curbing tropical forest loss. The carbon payments may complement these taxes, and an effective policy to combat tropical deforestation should jointly target forestry and cash-crop sectors. Article (**IV**) demonstrates the link between carbon compensation policies and land income taxation. An optimal carbon compensation scheme may require that national governments are allowed to use different compensation rates from that applied globally when passing national level compensations on to the local level. These results suggest that existing policies such as taxation should be accounted for in the analysis and design of international carbon policy instruments that aim at enhancing forests' role in climate change mitigation.

Keywords: Ageing, amenity preference, carbon payments, nonindustrial private forests, taxes, tropical deforestation

PREFACE

It is the climax of fulfilling a dream of doing a doctorate degree at a reputed foreign university that my parents, Chitta Ranzan Barua and Baby Barua, and my first paternal uncle Ananda Mohan Barua, a homeopathic doctor, and high school science and maths teacher, had been able to implant in me a long time ago. Still I would not pursue the degree in the very field of *forest economics*, if two things did not happen. First, if both my father and uncle did not persuade me to choose *forestry* over *chemistry* as the major in my undergrad, and second, if Professor Amartya Sen did not win a Nobel Prize in Economics. Professor Sen's winning the Nobel Prize hugely encouraged me to combine economics with forestry in my higher studies.

I do not have enough words to express gratitude to Jussi Uusivuori, my main thesis supervisor and Professor of Forest Economics and Policy, Finnish Forest Research Institute (METLA), and Jari Kuuluvainen, co-supervisor of my thesis, and currently Adjunct Professor (formerly Professor, 1997-2009), Department of Forest Sciences, University of Helsinki. It was Jussi who introduced me to the fascinating world of applying mathematics to solve resource and environmental economics problems. He has always had a very confident, calm and pleasing way of guiding me in research. Jari has been a wonderful teacher and an excellent supervisor to me. Both Jussi and Jari, two wonderful professors and human beings, have always had time for me to discuss about problems and issues related not only to my studies and research, but also to different areas of economics. Whenever I felt there was a barrier or I was ending up in a dead end situation in my research, Jussi and Jari showed me a way to get around or pass through.

I would like to extend my sincere gratitude to Olli Tahvonen, Professor of Forest Economics and Policy, Department of Forest Sciences, University of Helsinki for being my main professor, for heading my doctoral mentoring committee, and for his careful and assured handling of all processes from pre-examination to defense of the thesis. I would also like to thank Lauri Valsta, Professor of Forest Economics and Management, and Heimo Karppinen, Professor of Private Forestry, both at the Department of Forest Sciences, University of Helsinki for being in my doctoral mentoring committee.

A substantial part of the summary was written while I was a visiting doctoral student at the School of Forestry and Environmental Studies, Yale University, New Haven, USA. Discussion with Robert Mendelsohn, my academic host and Professor of Economics at Yale University helped me a lot to improve the quality of the summary and the fourth article. Thanks Rob for your kind help. Thanks also to the scientific committee of the 3rd Faustmann International Symposium held in Darmstadt, Germany in 28 – 31 October 2009 for giving me the Best Paper for Young Researchers Award for my second doctoral article. This has been a huge encouragement for my research.

I cordially thank the pre-examiners of my thesis, Professor Peichen Gong, Department of Forest Economics, Swedish University of Agricultural Sciences, Umeå, Sweden and Dr. Ville Ovaskainen, Senior Researcher, Finnish Forest Research Institute, Vantaa, Finland. Their thorough and careful reviewing, constructive criticism, and insightful comments and corrections helped me greatly improve the quality of my thesis.

I would like to thank Jani Laturi, researcher, METLA for co-authoring my first doctoral article and helping me with MATLAB codes for first three articles of the thesis. I would also like to thank Jussi Lintunen, researcher, METLA who not only co-authored the fourth article, but also helped me understand the mathematical formulation of the problem in that article better. I also express my sincere gratitude to Terese Forster for her suggestions to make the language of articles and title of the thesis more fluent, and to Kevin Kromash of Yale University for his suggestion concerning the title of the thesis.

I am grateful to the Helsinki University Center for Environment HENVI for providing me funding for last three years (2009-2011) of doctorate through its research program on Global Environmental Change. Cordial acknowledgement is also reserved for the Finnish Doctoral Program in Forest Sciences (GSForest) for funding the first year (2008) of my doctorate, and Metsämiesten Säätiö Foundation for partly funding my first doctoral article.

Dr. Olli Haltia, CEO of Dasos Capital is gratefully acknowledged for his showing tremendous interest in my research, encouraging me every time I met him and for being the key instrumental person for sending me to Yale University. I would also like to thank Jyrki Salmi, Senior Partner and Head of Forest Policy Consulting, Indufor Oy for his encouragement and support. My fellow colleagues and dear friends, Henna Lyhykäinen, Saeed Bayazidi, Dr. Lei Wang, Sami Niinimäki, Sampo Pihlainen, Gabriela Albaracín, Adrián Monge Monge, and Dr. Ashraful Alam, heartiest thanks to you all for cheering up for me all the time. My all other friends and well-wishers, too many to mention them all, thank you all so very much for your support.

Finally, my deepest affection finds my parents, Chitta Raznan Barua and Baby Barua, and rest of my extended family, paternal and maternal grandmothers, Shanti Bala Barua and late Neli Barua, respectively, paternal uncles, Sushen Bikash Barua and Ananda Mohan Barua, aunts, Mridula Barua, Konica Barua and Shika Barua, and maternal uncles, Prodip Barua, Gautam Barua and Uttam Barua. It has been their unconditional love and support that made me ever more determined to finish the degree. Bipul dada, Dipul, Tapos, Shawon, Maya didi, Daya didi, Sumita, Suborna, Shukla and Shukta, thanks and love to you all for your feeling proud of what I have been doing and making my journey worthwhile.

Sepul K. Barua
Helsinki, December 2011

LIST OF ORIGINAL ARTICLES

This doctoral dissertation is based on the following four articles, which are referred to by their Roman numerals in the text throughout this summary. Articles (**I – III**) are reprinted with the kind permissions of publishers and article (**IV**) is the author version of the submitted manuscript.

I **Barua, S. K.**, Kuuluvainen, J., Laturi, J. and Uusivuori, J. 2010. Effects of forest taxation and amenity preferences on nonindustrial private forest owners. European Journal of Forest Research. 129 (2): 163- 172. doi: 10.1007/s10342-009-0310-6.

II **Barua, S. K.**, Kuuluvainen, J. and Uusivuori, J. 2011. Taxation, life-time uncertainty and nonindustrial private forest-owner's decision making. Journal of Forest Economics. 17 (3): 267-284. doi:10.1016/j.jfe.2011.04.004.

III **Barua, S. K.,** Uusivuori, J. and Kuuluvainen, J. 2011. Impacts of carbon-based policy instruments and taxes on tropical deforestation. Ecological Economics. doi:10.1016/J.ECOLECON.2011.10.029.

IV **Barua, S. K.,** Lintunen, J., Uusivuori, J. and Kuuluvainen, J. 2011. On the economics of tropical deforestation: carbon credit markets and national policies. (manuscript)

AUTHOR'S CONTRIBUTION

The original ideas for the separate articles were suggested by Jussi Uusivuori and Jari Kuuluvainen. The author further developed these ideas into research problems jointly with Jussi Uusivuori and Jari Kuuluvainen. The numerical simulation models in Matlab for articles (**I**), (**II**) and (**III**) were jointly developed with Jani Laturi. The author gathered data for numerical analyses of articles (**I**), (**II**) and (**III**) and derived the numerical results. In article (**IV**), modeling ideas were developed and analytical results were derived jointly with Jussi Lintunen, Jussi Uusivuori and Jari Kuuluvainen. The author assumed the main responsibility of deriving the analytical results of articles (**I**), (**II**) and (**III**) and writing all four articles.

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1. INTRODUCTION

1.1 Background and motivation of the thesis

In perfect market conditions, taxes are used to collect public revenue, in which case their desired property is neutrality. Under market imperfections, they can be used to increase economic efficiency by correcting market failures. Taxes imposed in the forest sector, similar to those in other sectors, are an important public policy instruments and source of government revenue for public spending. Such taxes form the largest cost category for the private forest-owners in many parts of the world and thus may play a vital role in their forest harvesting and other economic decisionmaking.

The amenity services of forests such as carbon sequestration, scenic beauty, biodiversity and wilderness also affect decisionmaking of private forest-owners (e.g. Calish et al. 1978; Ovaskainen 1992; Kuuluvainen et al. 1996; Koskela and Ollikainen 1997) as demand for these services is increasing. Moreover, these services are being appreciated more by the private sector. Likewise, the age-distribution of forest-owners has effects on their harvesting and other decisionmaking, and determines timber stocking in their forests (Favada et al. 2007). Consequently, the amenity preferences and age of the forest-owners affect their objectives (e.g. Kuuluvainen et al. 1996; Favada et al. 2009), and also the effectiveness of forest taxation policies. Therefore, theoretical analysis of forest taxation that ignores the distribution of forest-owners based on their amenity preference and age may give misleading results.

A large number of forest economics studies dating back to Max and Lehman (1988) have examined the non-neutrality of different forest taxes under forest amenity valuation.[1] However, amenity preferences in those studies had entered the analysis only qualitatively without any measurement of their relative strengths. Therefore, the interlinkages between the effects of forest taxes and different forest-owners groups that are separated by the intensity of amenity preferences[2] have hitherto been absent. Moreover, earlier forest economics literature has not addressed the question of how the reaction to forest taxation varies across different age groups of forest-owners.

Taxes on income affect the level of forest harvesting, for example, in the presence of uncertainties (e.g. Koskela 1989a, 1989b; Ollikainen 1993), amenity valuation (e.g. Ovaskainen 1992; Uusivuori and Kuuluvainen 2008) and when a larger economy structure is integrated into the analysis (Kovenock 1986). An increase in forest income taxation can reduce the removal of forest biomass by limiting forest harvesting, which could contribute to increasing the biomass and carbon stock of standing forests. However, the increase in taxation could also be associated with a permanent decrease in the profit of timber investment and hence could discourage forestry investment itself. This, in turn, could lead to reduced biomass and carbon stock of forests in the long run (Wibe and Gong 2010).

On the other hand, carbon-based policy incentives, such as carbon payments or timber-cutting penalties may result in either keeping a forest standing for longer periods (e.g. van Kooten et al. 1995, Hoen and Solberg 1997, Uusivuori and Laturi 2007,

[1] A more detailed review of these studies is presented in the literature review section of Chapter 2.

[2] The intensity of amenity preference refers to the relative weight given by the forest-owners to amenity services of forests and timber. The relative utility weight of amenity services was incorporated in the theoretical models of Kuuluvainen et al. (1996) and Ovaskainen et al. (2006). These studies, however, did not discuss forest taxes.

Thompson et al. 2009) or lead to reduced thinning harvests (e.g. Pohjola and Valsta 2007). However, these are new or still non-existing policy instruments, and their effectiveness in enhancing the role of forests in climate change mitigation is yet to be proven. In contrast, taxes as policy instruments have been in place for a long time. Therefore, what role taxes can play in the presence of policy instruments that aim to regulate climate services from forests is an interesting and important question. More specifically, a better knowledge of the complementary functions between taxes and carbon-based policy incentives is needed to help choose the best policy options that should enhance the role of forests in climate change mitigation.

Previous literature that deals with the role in climate change mitigation of even-aged forests –mostly located in boreal and temperate zones– had addressed potential climate policy issues separately from forest policy aspects (e.g. Englin and Callaway 1993, van Kooten et al. 1995, Keeler 2005). In contrast, a wide array of studies on forest economics had assessed the impacts of certain policy measures such as taxes and subsidies on even-aged forests but without addressing the question of climate change (e.g. Koskela and Ollikainen 2001, Ovaskainen et al. 2006, Uusivuori and Kuuluvainen 2008). Similarly, the literature on tropical forests had analyzed the climate policy measures such as carbon payments to avoid deforestation without considering existing policies such as forestry income taxation (e.g. Börner and Wunder 2008, Pfaff et al. 2007). Conversely, the impacts of income taxes on the level of tropical forest resources management were examined but without addressing the question of climate change (e.g. Namaalwa et al. 2007, Anthon et al. 2008, Ruzicka 2010, Karsenty 2010). However, to the best of the author's knowledge, no study had investigated the joint impacts of taxes and climate policy instruments that target forests.

1.2 Objectives

The first purpose of this thesis is to analyze how the impacts of forest taxes vary among forest-owners who differ by their amenity preferences and by their age. The second purpose is to study how taxes could be combined with carbon policy instruments for curbing tropical deforestation. This thesis is based on four separate articles the objectives of which are given below.

The objective of article (**I**) is to investigate the effects of the profit and land value taxes[3] on nonindustrial private forest (NIPF) owners' clear-cutting and thinning decisions under amenity preference. More specifically, it examines how the tax effects vary at different intensities of forest amenity preferences of the forest-owners. Furthermore, the article analyzes a voluntary tax regime in which a lowered profit tax rate could be combined with a land value tax as a win-win alternative to a forest tax regime with a profit tax but no land value tax.

The key question in article (**II**) is what the impacts of the capital income and inheritance taxes imposed on forest and non-forest assets[4] are on NIPF owners' harvesting

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[3] The *profit tax* is defined as a proportional tax on the net timber sales income, and the *land value tax* as a lump-sum tax levied on a set value of the forestland.

[4] The tax imposed on timber bequests is called the *inheritance tax on timber assets*, whereas that imposed on non-forest (i.e., external assets) bequests is called the *inheritance tax on external assets*. The *capital income tax on forest assets* is based on timber sales income net of the replanting cost and is therefore equivalent to the proportional profit tax discussed in the forest economics literature. The *capital income tax on external assets*, on the other hand, targets the capital income from monetary savings.

and consumption behavior under life-time uncertainty. More specifically, this article deals with the question of how the impacts of taxes on harvesting and consumption behavior change among different age-groups of forest-owners with valued forest amenities.

The objective of article (**III**) is to answer the question of how effective the carbon payment and taxes on forestry and cash-crop incomes are in combating tropical forest loss by analyzing data from the Chaco eco-region of Paraguay. The article also addresses how the rate of required carbon payments and land prices change as more privately held tropical forests are targeted for conservation.

Article (**IV**) contributes to modeling the economics of tropical deforestation under carbon crediting options for standing forests. This article also investigates optimal policies in terms of carbon compensation and land income taxation that would ensure a socially desired level of tropical forest resources.

1.3 Key contributions of the thesis

The contributions of the articles of this thesis are related to both the theoretical modeling of forest-owner's behavior and economics of tropical deforestation, and to forest policies and policies that regulate climate services from the forest sector. The policy related contributions of this thesis are as follows. First, article (**I**) shows that the profit and land value taxes affect only those forest-owners who value both timber production and forest amenity benefits. Conversely, these taxes do not affect the decisions of those forest-owners who clearly prefer either timber production or amenity benefits. Second, it is shown in article (**II)** that the reactions of forest-owners to capital income and inheritance taxes that target forest and non-forest assets vary across different age-groups. Third, article (**III**) demonstrates that taxes, *per se*, may be ineffective in curbing tropical deforestation, but carbon payments could complement taxes. Moreover, it is shown that taxes on forestry income have a very minimal impact on the rate of carbon payments needed to bring more privately held tropical forest under conservation. Finally, article (**IV**) shows that a national carbon compensation policy to save tropical forests is crucially dependent on pre-existing land income taxation. The taxation may make it optimal for a national government to apply different rates of carbon compensation than it received from the international community (e.g. in a REDD (Reducing Emissions from Deforestation and Degradation) -type of arrangement) in compensating the local carbon service providers such as a community that has right to tropical forests.

The theoretical models used in articles (**I**) and (**II**) to illustrate the behavior of forest-owners are the first applications of the forestland-based modeling approach (Uusivuori and Kuuluvainen 2005, 2008) in the two-period framework. In the two-period forestland models used in articles (**I**) and (**II**), the harvesting decision variable targets forestland area, instead of timber volume, as in the two-period biomass harvesting model used in the earlier literature. This allows one to account for – within a two-period framework – the value of new growth on land cleared in the first period, which can be considered as representing the land costs. Moreover, by specifying the forest area as a decision variable, these models can explicitly identify the specific harvesting methods and thus are also able to incorporate the age-class structure of the forests, which the two-period forestry models used in earlier literature had ignored. Another contribution of article (**I**) is that the two-period forestland model used in this article distinguishes harvesting between thinning and clear-cutting. Theoretical contributions of article (**II**) are, first, that it incorporates the impacts of the age of forest-owners when analyzing the effects of taxes. Second, it outlines a way to circumvent the conceptual question of what happens, at the occurrence of passing away of a forest-owner, to his assets that were not planned to be bequeathed. Such a question is kept open in the earlier literature. The model allows for the forest-owner to bequeath all his assets that are left at the time of his death, instead of *a priori* deciding on the exact size of bequests. Article (**III**) applies a market equilibrium framework to tropical deforestation problem, which had not been done in the economics literature concerning tropical forests. In addition, article (**IV**) contributes to the economics of deforestation by presenting an infinite-horizon dynamic optimization model with carbon crediting option of tropical forests.

The remainder of the summary proceeds as follows. The next chapter reviews the models that form the theoretical basis for the separate articles, followed by a review of earlier literature. Chapter 3 presents the methodologies applied and the special features of the models used in, and results of separate articles. Discussion and conclusions are presented in Chapter 4.

2. THEORETICAL FRAMEWORK AND EARLIER LITERATURE

2.1 Theoretical models

2.1.1 Faustmann rotation model

The Faustmann rotation model – also known as the optimal forest rotation model – determines the optimal time to cut an even-aged forest stand or the optimal forest rotation length. In a basic Faustmann rotation model, timber volume (or yield) of an even-aged stand is described as the function of the stand age so as to maximize the net present value of an infinite chain of successive rotations by choosing the optimal harvesting age. The optimality condition of the model suggests cutting the forest when the marginal value increment of forest equals the opportunity cost, i.e. the interest on the value of standing stock and forest land (see e.g. Samuelson 1976, and Johansson and Löfgren 1985, p.73- 80).

The classical Faustmann model is based on a set of assumptions as identified by Samuelson (1976). The model assumes that the stumpage prices and future interest rates are constant and known, the growth function of stands is known, the markets for forestland and financial capital are perfect. Furthermore, the model considers timber as the only output of forest and ignores all other non-timber products and services, and each forest stand as a completely separate unit free of any influence from neighboring stands. The model has been extended to relax these assumptions, by introducing, *inter alia*, non-timber values, i.e. amenity values of forests (e.g. Hartman 1976, Strang 1983, Bowes and Krutilla 1985, Salo and Tahvonen 2002a), non-linear harvesting costs (e.g. Heaps 1984), endogenous timber prices (e.g. Mitra and Wan 1985, Salo and Tahvonen 2002b, 2003) and imperfect capital markets (e.g. Tahvonen et al. 2001).

2.1.2 Two-period model of a utility maximizing forest-owner

The earliest case of applying a two-period framework to forestry problems dates back to Binkley (1980). However, the commonly known two-period biomass harvesting forestry models are not of the type described in Binkley (1980), rather they are extensions of the Fisherian consumption-saving model, and were introduced by Löfgren and Johansson (1982) and Lohmander (1983). Next, first a basic version of the two-period model of a utility maximizing forest-owner who does not value forest amenities is presented closely following Kuuluvainen (1990). This basic version with extensions has been extensively used in forest economics literature (e.g. Max and Lehman 1988, Koskela 1989a, b, Ollikainen 1990, 1991, 1993, 1996, Ovaskainen 1992, Kuuluvainen et al. 1996). After the biomass model, a simplified version of the two-period forestland models used in articles (**I**) and (**II**) is presented. This model operates with forestland area and incorporates forest amenity preferences by weighing the importance given by the forest-owners to forest amenities and timber benefits.

(*i*) Basic two-period biomass harvesting model

Assume that the forest-owner maximizes his utility from consumption over two periods (c_t, c_{t+1}). The utility function is increasing and concave, i.e., $u'(.)>0$ and $u''(.)<0$, and is additively separable between the time periods. The utility maximization problem of the forest-owner can be given as:

$$\max U = u(c_t) + \frac{1}{1+\rho} u(c_{t+1}) \qquad (1)$$

Subject to

$$c_t = p_t h_t + w_0 - w_t \qquad (2)$$

$$c_{t+1} = p_{t+1} h_{t+1} + (1+r) w_t \qquad (3)$$

$$h_{t+1} = (Q - h_t) + g(Q - h_t) \qquad (4)$$

The periodic utility is realized at the beginning of each period. The utility in the second period is discounted at the rate of forest-owner's subjective time preference ρ, which is strictly positive. At the beginning of the first period t, the ownership consists of a total standing timber stock of Q cubic meter, m^3 and a financial asset of w_0. The decisions the forest-owner faces at the beginning of period t are how much of the standing stock to harvest, denoted by h_t ($0 \le h_t \le Q$) and how much money to save, denoted by w_t (saving if $w_t > 0$, borrowing if $w_t < 0$). This implies that the harvesting parameter, h_t, targets the forest biomass or timber volume. The model ignores the age-class structure of the forests.

The consumption of the forest-owner in the current period, as given by (2), originates from the timber selling revenue, $p_t h_t$, where p_t is the timber price net of harvesting costs in period t, and changes of financial assets $(w_0 - w_t)$. The planning horizon of the forest-owner ends in the second period, t+1, and thus his consumption constraint (3) consists of the value of the second period timber stock and of the principal and interest on savings made in the first period, $(1+r)w_t$.[5] Here p_{t+1} is the timber price net of harvesting costs in period t+1 and r is the market interest rate. Equations (2) and (3) give the periodic budget constraints of the forest-owner. The timber stock harvested in period t+1, as given by (4), contains the stock not harvested in period t, i.e. $(Q - h_t)$ and growth on that stock over one period, i.e.

[5] In the basic model the forest-owner does not have any bequest motive.

$g(Q - h_t)$. The growth function is concave on the standing timber stock after the first period harvesting i.e. $g' > 0$ for $0 < (Q - h_t) < Q_{MSY}$, $g' < 0$ for $(Q - h_t) \geq Q_{MSY}$, and $g'' < 0$, where Q_{MSY} is the timber volume at maximum sustained yield.

The optimal consumption rule of the forest-owner is derived by substituting (2 – 4) into (1) and taking the derivative with respect to (w.r.t.) the net saving, w_t:

$$\frac{u'(c_t)}{u'(c_{t+1})} = \frac{1+r}{1+\rho} \tag{5}$$

The rule (5) implies that when the subjective time preference rate of the forest-owner equals the market interest rate, then his marginal utilities of consumption in both periods and also the periodic consumption levels are equal. It can further be seen from (5):

$$\text{if } r < \rho ,\ c_t > c_{t+1} \text{ and if } r > \rho ,\ c_t < c_{t+1} \tag{6}$$

Condition (6) implies that when the subjective time preference rate of the forest-owner is higher than the market interest rate, then current consumption, c_t, is larger than future consumption, c_{t+1}, and the opposite holds when the market interest rate is higher than the time preference rate. Assuming an interior solution, the optimal harvesting rule of the forest-owner can be expressed as:

$$p_t(1+r) = (1+g')p_{t+1} \tag{7}$$

where g' is the growth rate of forest biomass.

The left hand side (LHS) of (7) represents the marginal benefit of current harvesting and the right hand side (RHS) the marginal cost of it. The marginal benefit is the revenue from harvesting one m^3 more timber in period t, and the marginal cost is the revenue to be earned from harvesting that one more m^3 of timber in the following period, $t+1$. It can be noted that the marginal utility terms are absent in (7), which implies that the harvesting and consumption decisions are separable from each other.

(*ii*) Two-period forestland model with forest amenity valuation

Next, a simplified version of the model used in articles (**I**) and (**II**) of this thesis is presented. In the model, the harvesting decision is specified for the forestland area where timber is cut down, rather than the timber volume as in the basic version described earlier. Furthermore, an amenity sub-utility function is included. The utility maximization problem of the forest-owner under a perfect capital market is given as:

$$\max U = (1-\alpha)\left[u(c_t) + \frac{1}{1+\rho}u(c_{t+1})\right] + \alpha\left[A(Q_t) + \frac{1}{1+\rho}A(Q_{t+1})\right] \tag{8}$$

Subject to

$$c_t = (p_t q_i - k)ax + \overline{w} - w_t \tag{9}$$

$$c_{t+1} = [p_{t+1}q_1 a + p_{t+1}q_{i+1}(1-a) - k]x + (1+r)w_t \tag{10}$$

$$q_{i+1} = (1 + f_i')q_i \qquad (11)$$

$$Q_t = q_i x \qquad (12)$$

$$Q_{t+1} = q_1 ax + (1-a)q_{i+1}x \ . \qquad (13)$$

where the amenity utility function is also assumed to be strictly concave, i.e., $A'(.) > 0$ and $A''(.) < 0$. Harvesting in the first period increases utility from consumption of goods and services, but decreases utility from forest amenities in the second period by reducing the standing stock. This makes timber production and consumption decision nonseparable. In (8) α ($0 \le \alpha \le 1$) refers to the amenity preference that measures the relative weight given by the forest-owner to amenity and consumption utilities. The larger the value of α, the more emphasis is laid by the owner on the forest amenities. It can be noted that the amenity utility part in the above maximization problem (8 –13) is specified in such a way that the loss of amenity utility in the first period is experienced only in the second period.

At the beginning of the current period *t*, the forest-owner owns a financial asset, $\overline{w}$, and x hectares of forestland with *i* period old stands that contains q_i cubic meters of timber per hectare. In contrast to the basic version of the two-period biomass harvesting model presented in the earlier section, at the beginning of period *t* the forest-owner decides to harvest a share a ($0 \le a \le 1$) of his forestland and save w_t amount of money (saving if $w_t > 0$, borrowing if $w_t < 0$). Using this formulation the model can be generalized to an infinite-time horizon model with any number of age classes and be applied to study the standard Faustmann rotation problem (Uusivuori and Kuuluvainen 2005). This is not the case with the biomass harvesting model. The harvesting share is given as a percentage of the forestland and hence targets the hectares of forestland. This implies that the harvesting method followed is clear-cutting.[6] The model being described in this section and the models used in articles (**I**) and (**II**) are the first applications of a forestland-based modeling approach in two-period framework.

In period *t*, the forest-owner clear-cuts ax hectares to earn a harvesting income of $(p_t q_i - k)ax$ and leaves (1-a)x hectares for the next period, t+1, where p_t is the timber price per m^3 in period *t*. He replants the harvested area at a cost of *k* per ha (assuming that $p_t q_i > k$). Therefore, the first period consumption of the forest-owner consists of timber harvesting income net of the replanting cost and a net saving (9).

The consumption in period t+1 consists of timber harvesting income and the principal and interest of the savings made in period *t*, i.e., $(1+r)w_t$, where *r* is the market interest rate (10). The timber harvesting income comes from the clear-cutting of *old-growth* forest, $p_{t+1}q_{i+1}(1\text{-}a)$ and the *new-growth* forest, $p_{t+1}q_1a$, where p_{t+1} is the timber price per cubic meter in period t+1. Replanting costs of *k* per *ha* are assumed for both types of forests.[7] The old growth consists of stands that grow on a site not harvested in the current period and hence are i+1 periods old in the next period, and have q_{i+1} cubic meters of timber per hectare. On the other hand, the new growth stands grow on a site harvested in the current period and hence are just one period old in the subsequent period, and contain q_1 cubic meters of timber per hectare assuming that $q_{i+1} > q_1$. When the forest-owner decides

[6] In article (**I**) of this thesis an extension is made where the model features both clear-cutting and thinning.

[7] It can be assumed that at the end of the second period, another two-period cycle starts and the cycle is repeated over time. This implies the land remains in forestry use and is replanted after every clear-cutting.

whether or not to harvest in the current period, his opportunity cost of not harvesting also includes the income from the land to be freed by harvesting. Therefore, the value of new growth, $p_{t+1}q_1a$, is an opportunity cost of not harvesting the forest in the current period. The growth of forest from one period to another is linear with a constant rate of growth f_i' ($f_i' > 0, f_i'' = 0$), a rate given as a constant percentage of per ha volume of forest from the current to the next period. Here sub-script i indicates that the growth rate is connected to the age of forest.

The optimal consumption rule in this model is the same as in the basic version given by (5). However, assuming an interior solution, the optimal harvesting rule is different and can be given as:

$$(p_t q_i - k)(1+r) + p_{t+1}q_1 = p_{t+1}q_{i+1} + \frac{\alpha}{1-\alpha}\frac{A'(Q_{t+1})}{u'(c_{t+1})}(q_{i+1} - q_1) \qquad (14)$$

In (14), the LHS is the marginal benefit and the RHS is the marginal cost of forest harvesting in period t. The first term on the marginal-benefit side is the revenue net of the replanting cost from harvesting, i.e. clear-cutting one *ha* of i period old forest in period t, whereas the second term is the revenue from clear-cutting one *ha* of new-growth forest in period t+1. The second term indicates that the new growth forest is the opportunity cost (opportunity benefit) of not clear-cutting (clear-cutting) forest in period t. The first term on the RHS of (14) is the revenue from harvesting one *ha* of forest in period t+1, and the second term, $\frac{\alpha}{1-\alpha}\frac{A'(Q_{t+1})}{u'(c_{t+1})}$ can be interpreted as the relative marginal amenity utility to the forest-owner. Because the marginal amenity utility term is affected by the consumption level, the presence of this term in the harvesting decision rule implies that the harvesting decision of the forest-owner is not separable from his consumption decision. This term adds up to the marginal cost of current harvesting, which implies that the marginal cost of current harvesting is larger when the amenity valuation is considered than when it is ignored. This indicates that the amenity valuation of the forest owner works toward decreasing the current harvesting. This can formally be shown using (14). Since $u'(.), A'(.) > 0$ as per assumption, for any non-zero amenity preference the relative marginal utility term is positive. Therefore, for $\alpha > 0$ and $A'(.) > 0$:

$$(p_t q_i - k)(1+r) > p_{t+1}(q_{i+1} - q_1) \Rightarrow (1+r) > \frac{p_{t+1}(q_{i+1} - q_1)}{(p_t q_i - k)} \qquad (15)$$

This rule suggests that the marginal rate of return on the growing stock is smaller than the market rate of interest when forest amenities are present. This, in turn, implies that the optimal growing stock remains greater. Therefore, a smaller amount of timber is harvested in the first period to leave a larger forest resource for the second period. Consequently, the amenity valuation of the forest owner decreases the current harvesting.

2.1.3 Dynamic optimization model for tropical deforestation

In the literature, various types of models that explain the economics of deforestation are extensively used. Walker and Smith (1993) and Mateo (1997) respectively used optimal stopping and optimal control models to analyze the tropical-forest clearing policy of a private agent. Bulte and van Soest (1996) applied a dynamic modeling approach and demonstrated that encroachment by shifting cultivators may save virgin tropical forests from being cleared by concessionaires. Furthermore, analyses using dynamic models showed that tropical deforestation decreases as the property rights become more secure (Mendelsohn 1994, Amacher et al. 2009) and non-timber benefits from forests increase (Amacher et al. 2009). However, tropical deforestation increases with greater corruption and dependency of local people on forests (Barbier et al. 2005), and rising agricultural prices and profit from marketing timber (Hartwick et al. 2001).[8] An infinite horizon dynamic optimization model that explains the economics of tropical deforestation is presented below. This model is a simplified version of the model used in article (**IV**) and also features the core concept of the model used in article (**III**).

Assume that in the beginning of a period $t \in \{t_0, t_0+1, t_0+2, ...\infty\}$, the agent, who could be a private individual, firm or indigenous community, owns x_t ha of tropical forest with a timber stock of q $m^3 ha^{-1}$. The agent maximizes his utility over an infinite time horizon by choosing the optimal rate of forest clearing in each period. Utility is derived from both monetary value of consumption (c_t) and the amenity services originated from the standing forest stock (Q_t). Both the consumption $u'(.)$ and amenity $A'(.)$ utilities are increasing and concave functions of their respective arguments, i.e. $u'(.), A'(.) > 0$ and $u''(.), A''(.) < 0$. The utility function satisfies the Inada conditions, and is additively separable between consumption and amenity utilities as well as among time periods. The consumption of the agent is limited by a budget constraint in which the present value of consumptions in all periods does not exceed his forestland value, $LV_{t_0}(.)$ perceived in initial period t_0 (explained later in this section) and external asset w_{t_0} in that period. The agent's expected utility maximization problem at the beginning of period t_0 can be given as:

$$\underset{\{a_t, c_t\}_{t=t_0}^{\infty}}{Max} U_t = \left[E_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} \left[u(c_t) + A(Q_t) \right] \right] \quad (16)$$

Subject to

$$\sum_{t=t_0}^{\infty} \delta^{t-t_0} c_t \le w_{t_0} + LV_{t_0}(x_{t_0}, \boldsymbol{a}_{t_0} p_{t_0}^{tim}, \mu_{t_0}) \quad (17)$$

$$Q_t = (1-a_t) q x_t \quad \forall t \quad (18)$$

$$x_{t+1} = (1-a_t) x_t \ \forall t \quad (19)$$

where, $\beta = (1+\rho)^{-1}$ and $\delta = (1+r)^{-1}$, ρ and r are the time discount and market interest rates, respectively both of which are strictly positive, and (19) gives the forestland area dynamics. Future utilities are considered as expected utilities formed in

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[8] Static models were also used to explain the economics of tropical deforestation under competitive land-use options, for example, by Barbier and Burgess (1997), Hardie and Parks (1997), Parks et al. (1998), Alix-Garcia (2007), Amacher et al. (2009, p. 166-173) and Angelsen (2010). For comprehensive reviews of analytical and other models of tropical deforestation, see also Kaimowitz and Angelsen (1998), Angelsen and Kaimowitz (1999), Angelsen (1999) and Amacher et al. (2009, p. 163-165).

current period, t_0, and E_{t_0} is the expectation operator. The forestland value depends on current and expected future clearing decisions, i.e., $\boldsymbol{a}_{t_0} = \{a_{t_0}, a_{t_0+1}, ...\}$. This is explained next.

The tropical forest stock is assumed to be non-renewable. It can be justified by the fact that once the forestland in tropics is cleared, it permanently goes to other uses such as agriculture. This fact is reflected in the forestland area dynamics given by (19). The agent's revenue from forest clearing comes from selling timber as well as selling the cleared land to other uses. He also receives an income from selling non-timber products procured from uncleared forests such as mushrooms, berries and honey. [9] Let, p_t^{tim} be the timber price per m^3, p_t^l the price per ha of cleared forestland and k_t the forest-clearing (e.g. from slash and burn) cost per ha, and μ_t the non-timber income net of any procurement cost from each ha of uncleared forest in period t. We assume that only the first period timber and cleared land prices, non-timber income and forest clearing costs are known, but those in all future periods are uncertain and follow a trend-stationary process. Therefore, all future prices, revenues and costs are considered as expectations. The land value to the agent in the current period t_0 is the present value of expected profit flows derived from the forest, and can be given as:

$$\begin{aligned} & LV_{t_0}(x_{t_0}, \boldsymbol{a}_{t_0}, p_{t_0}^{tim}, \mu_{t_0}) \\ & = \left[a_{t_0}\left(p_{t_0}^{tim} q - k_{t_0} + p_{t_0}^{l}\right) + \left(1 - a_{t_0}\right)\mu_{t_0}\right] x_{t_0} \\ & + E_{t_0} \sum_{t=t_0+1}^{\infty} \delta^{t-t_0} \left[a_t\left(p_t^{tim} q - k_t + p_t^{l}\right) + \left(1 - a_t\right)\mu_t\right] x_{t_0} \prod_{s=t_0}^{t-1}\left(1 - a_s\right) \end{aligned} \tag{20}$$

On the RHS of (20), the first term gives the profit flow realized in period t_0, and the second term gives sum of net the expected profit flows generated in all future periods as perceived in period t_0. The profit flow in each period consists of incomes from forest clearing net of clearing costs and non-timber forest products sale. The optimal consumption and clearing rules are derived by using the Lagrangian multiplier and by solving the Karush-Kuhn-Tucker conditions necessary for the optimum. The optimal consumption rule can be given as:

$$E_{t_0}\left(\frac{\beta}{\delta}\right)^{t-t_0} u'(c_t) = \lambda \quad \forall t \tag{21}$$

In (21) the Lagrange multiplier λ gives shadow price of the expected marginal utility of consumption in period t. The optimal consumption rule can more generally be given as:

$$u'(c_{t_0}) = E_{t_0}\left(\frac{\beta}{\delta}\right)^{t-t_0} u'(c_t) \tag{22}$$

[9] Carbon sequestration and other environmental services such as biodiversity and watershed regulations can also be seen as non-timber produce of tropical forests.

The above consumption rule can be explained in the same way as the rule in two-period model given by (5). Assuming an interior solution, the optimal forest clearing rule for a period *t* perceived in t_0 can be given as:

$$
\begin{aligned}
&E_{t_0}\delta^{t-t_0}\left(p_t^{tim}q-k_t+p_t^l\right)\\
&=E_{t_0}\delta^{t-t_0}\left[\mu_t R_t^c+\sum_{u=t+1}^{\infty}\delta^{u-t}\left[a_u\left(p_u^{tim}q-k_u+p_u^l\right)+(1-a_u)\mu_u\right]\prod_{v=t+1}^{u-1}(1-a_v)\right] \quad (23)\\
&+E_{t_0}\left\{\beta^{t-t_0}\frac{1}{\lambda}\left(A'(Q_t)+\sum_{u=t+1}^{\infty}\beta^{u-t}A'(Q_u)\prod_{v=t+1}^{u-1}(1-a_v)\right)q\right\}
\end{aligned}
$$

The left hand side (LHS) of (23) represents the marginal benefits of forest clearing, whereas the RHS represents the marginal costs. As the rule suggests, besides the amenity services, the current non-timber income and all future incomes are the opportunity cost, i.e. marginal cost for current forest clearing.

The time dimension of the solution regarding consumption (21 and 22) and forest clearing (23) has to be understood in the following way. The actions for the current period $t=t_0$ are performed as the optimality conditions state. For the future periods $t>t_0$ the optimality conditions present the expected decisions given by information at $t=t_0$. These expected actions induce expected values for the monetary wealth and land value. The decision problem is solved in every period as the new realizations for the random variables are observed.

The supply-side model of article (**III**) is a two-period application of the model presented above with the option values that originate from carbon crediting and land income taxation incorporated. In article (**IV**) the above model is extended to incorporate carbon crediting option of tropical forests and land income taxation.

2.2 Literature on taxation and climate policy instruments targeting forests

2.2.1 Forest taxation under amenity valuations

The effects of common forest taxes, which most notably include yield, site productivity and *ad valorem* property taxes on the harvesting behavior of a forest-owner who considers amenity values of forest side-by-side timber have been studied in a two-period framework by Max and Lehman (1988), Ovaskainen (1992), Koskela and Ollikainen (1997), and Amacher et al. (1998). [10] Moreover, Amacher and Brazee (1997) described a forest-owner's behavior using a two-period model with forest taxes and amenity valuation. In addition, Koskela and Ollikainen (2001, 2003) used the optimal rotation model, and Uusivuori and Kuuluvainen (2008) used the age-class model to study the effects of forest taxes on timber harvesting under the amenity valuation. These studies showed that the amenity valuation of forest-owners break the neutrality of the common forest taxes concerning forest harvesting. However, none of these studies addressed the question of how the effects of forest taxes vary at different intensities of amenity valuation by the forest-owners. These studies also

[10] For the sake of completeness, the literature that either reviewed earlier forest taxation literature or studied forest taxation without considering amenity valuations is presented in Table 1.

did not examine forest tax effects within a framework that combines both thinning and clear-cutting harvests. These two aspects are investigated in the article (**I**) of this thesis.

2.2.2 Taxation and the bequest motive

The literature on the bequest motive and inheritance taxes on NIPF owner's decision making is scant. The effects of the bequest motive, in the absence of any tax, on forest capital stock development were discussed by Löfgren (1991), Hultkrantz (1992) and Tahvonen (1998). Ollikainen (1998) and Amacher et al. (1999) investigated the effects of the inheritance and forestry taxes upon NIPF owners' harvesting and bequeathing decisionmaking. Further, Amacher et al. (2002, 2003) studied the effects of an optimal mix of bequest and harvest taxes on the bequeathing behavior of private forest-owners. However, this literature did not address the question of how the effects of forest and bequest taxes vary across different age-groups of forest-owners, which is the aim of article (**II**) of this thesis.

2.2.3 Carbon policy instruments and taxes to regulate climate services from forests

The effects of policy incentives for carbon sequestration on optimal forest rotation are discussed by, for example, Englin and Callaway (1993), Adams et al. (1999), Murry (2000), Sohngen and Mendelsohn (2003), Chladná (2007), Sohngen and Brown (2008) and Asante et al. (2011). Furthermore, the effect on optimal rotation or timber yield of policy program where the forest carbon sequestration by keeping forest standing is subsidized and the carbon release by harvesting is taxed is discussed by van Kooten et al. (1995), Hoen and Solberg (1997), Pohjola and Valsta (2007), and Thompson et al. (2009). In addition, Uusivuori and Laturi (2007), and Guthrie and Kumareswaran (2009) investigated the effects of carbon payments on private forest-owners' decisionmaking. These studies focused on even-aged forests.

There are a handful of studies analyzing the impacts of carbon-based policy instruments that target forests in the tropics. Hunt (2008) discussed the role of carbon incentives on private reforestation in tropical Australia. Börner and Wunder (2008) discussed paying for avoided deforestation in the Brazilian Amazon, whereas Pfaff et al. (2007) empirically studied the conservation of tropical forests for carbon benefits from the Costa Rican perspective. Apart from these, a number of studies (e.g. Bulter et al. 2009, Naidoo et al. 2009, Persson and Azar 2010) discussed the role of carbon payment in combating tropical deforestation. None of the studies discussed in this section (2.2.3) have, however, included any taxes. Likewise, the taxation literature reviewed in the last two sections and in Table 1 has ignored the climate policy instruments. Article (**III**) of this thesis analyzes the joint impacts of taxes and carbon-based instruments on tropical forest clearing and land price in a market equilibrium framework.

2.2.4 Optimal design of taxes and carbon-based policy instruments for forests

The design of optimal forest taxation in the presence of amenity valuation and bequest motive was discussed, for example, in Amacher and Brazee (1997) and Amacher et al. (2002). A small number of studies also investigated the design of optimal carbon incentive programs for forests. Tahvonen (1995) and Romero et al. (1998) presented comprehensive approaches to calculate the rate of carbon subsidy/tax needed to ensure the social optima of forests. Englin and Klan (1990) and Koskela and Ollikainen (1997, 2003) examined the optimal mix of forest taxes to correct the negative externalities to society caused by harvesting and hence to equate the private optima with the social optima. However, these studies did not explicitly focus on tropical forests. Moreover, these studies did not discuss the design of a carbon policy instruments by taking into account any pre-existing taxation policies that focus, for example, on income from tropical forestland, as done in article (**IV**).

Table 1: Studies that reviewed earlier taxation literature and investigated the effects of forest taxation without considering amenity valuation

Study	Modeling framework	Topic
Literature review or general studies		
Amacher (1997)	-----	Review of forest taxation literature
Karsenty (2010)	-----	Forest taxation that focuses on tropical forests in Central Africa
Ruzicka (2010)	-----	Forest taxation from tropical forest point of view
Studies without considering amenity valuation		
Klemperer (1976)	Optimal rotation	Tax effects on optimal rotation length
Klemperer (1978)	Optimal rotation	Timber tax equity criteria in setting forest property tax levels
Chang (1982)	Optimal rotation	Taxation effect on optimal forest rotation
Chang (1983)	Optimal rotation	Taxation effect on optimal forest rotation
Kovenock (1986)	Optimal rotation	Effect of land value and income taxation in an Austrian sector of economy
Koskela (1989a)	Two-period	Tax effects on timber supply under timber price uncertainty
Koskela (1989b)	Two-period	Tax effects on timber supply under price uncertainty and credit rationing
Ollikainen (1990)	Two-period	Forest taxation effect on timber supply under interest rate uncertainty and perfect or credit rationed capital market
Olllikainen (1991)	Two-period	Effects of taxes that target non-forest assets on timber supply under timber price uncertainty
Ovaskainen (1992)	Two-period	Forest taxation effect on timber supply and forest management intensity
Ollikainen (1993)	Two-period	Forest taxation and timber supply under interest rate and future timber price uncertainty
Ollikainen (1996)	Two-period	Forest taxation effects on timber supply under endogenous credit rationing
Uusivuori (2000)	Multi-period utility maximization	Neutrality of income taxation in an Austrian sector economy
Conrad et al. (2005)	Multi-period dynamic	Tax effects on tropical forest harvesting
Namaalwa et al. (2007)	Dynamic bio-economic	Impacts of taxes imposed on forestry income on the level of forest resources utilization in Uganda
Alvarez and Koskela (2007)	Optimal rotation	Effects of forest taxes on optimal rotation under stochastic stand value and risk aversion or neutrality
Anthon et al. (2008)	Single-period utility maximization	The impacts of taxes imposed on forestry income on the level of forest resources utilization in Tanzania.

3. METHODOLOGIES AND RESULTS OF SEPARATE ARTICLES

3.1 Amenity preference and taxation on non-industrial private forest-owners

In article (**I**) a utility-maximizing forestland model of a forest-owner with amenity preference is used. The model includes profit and land value taxes, and incorporates two different forest harvesting decisions into the two-period framework. The harvesting decisions are made sequentially in such a way that, first, the forest-owner decides how much of his forest area to clear and second, how much of the remaining standing volume to thin. In contrast to the two-period biomass harvesting models which were used in earlier forest economics literature (e.g. Kuuluvainen 1989, Koskela 1989a, b, Ollikainen 1990, 1991, 1993, 1996, Ovaskainen 1992, Kuuluvainen et al. 1996) article (**I**) identifies clear-cutting and thinning harvest explicitly. The new growth on cleared land is an opportunity cost of not clear-cutting in the first period, and thus it can be considered to represent land costs (as discussed in Section 2.1.1). By considering the new growth, the model also describes a forest in the second period with two age-classes. In addition, in this model a solution where the old-growth is only thinned is possible. The forest growth described in the model consists of an age-class dependent, constant intrinsic growth, and induced growth. The induced growth is concave, and depends on thinning intensity.

The comparative statics effects of taxes on both harvesting types are derived following Varian (1992, p. 491-492). The analytical comparative statics results give the qualitative effects of taxes on clear-cutting and thinning harvests under the amenity preference of the forest-owner. By using the case of a typical NIPF owner in Finland, the numerical analysis showed how these tax effects vary at different intensities of amenity preference of the forest-owners.

The numerical results show that both with no or very small intensity of amenity preference and with exclusive intensity of amenity preference, the NIPF owners behave similarly with or without the profit and land value taxes, i.e. the taxes are neutral to both clear-cutting and thinning decisions. Consequently the taxes do not influence the harvesting decisionmaking of those NIPF owners who are biased toward either timber harvesting or the amenity values of forests. Under small to medium intensities of amenity preference, i.e. when the forest-owner is relatively balanced between timber and amenity objectives, the profit tax decreases the optimal clear-cutting volumes. However, the effect on thinning may be positive or negative, depending on the level of intensity of amenity preference. The net effect of the profit tax is negative on the short-run timber supply of forest-owners who are relatively balanced between timber and forest amenities. The effects of the land value tax on clear-cutting and thinning harvests for the same forest-owners' group are opposite to the corresponding effects of the profit tax. These all imply that the taxes affect only those NIPF owners who are relatively balanced between timber production objectives and amenity benefits. In addition, it is shown analytically that the popularity of thinning increases over that of clear-cutting with the increase of the intensity of amenity preference to a point at which the forest-owner ceases clear-cutting and substitutes thinning for it.

The numerical analysis in article (**I**) demonstrates that a voluntary tax regime with a lowered profit tax combined with a land value tax may bring Pareto-improvement to a regime with profit tax but without a land value tax. In the proposed tax regime, under a certain range of intensities of amenity preference, a government can increase its tax revenue collection while the NIPF owners can have increased utility contrast to the current regime. This indicates that whether the win-win situation arises, crucially depends on the distribution of amenity intensity among the NIPF owners. The analysis also shows that the range of intensities of amenity preference that gives rise to the win-win situation changes its location and size as the timber price changes. This highlights the importance of considering both the amenity preference intensities and the fluctuation in timber prices to identify which party gains and which party loses when planning possible tax regime changes.

3.2 Taxation, life-time uncertainty and nonindustrial private forest-owner's decision making

Article (**II**) uses a two-period utility maximizing forestland model of a forest-owner with amenity preferences, focusing on clear-cutting only. The model incorporates capital income and inheritance taxes on forest and non-forest assets. Moreover, as a new feature in forest economics literature, the forest-owner's perceived probability of surviving through a future period is included in the model. The decreasing probability of survival in the model is a proxy for forest-owner's ageing. The higher is the survival probability, the younger is the forest-owner, and the lower is the survival probability, the older is the forest-owner. Therefore, the survival probability allows the analysis of the effect of forest-owner's age on consumption and harvesting, in addition to the effects of taxes among different age groups of forest-owners. Moreover, besides the consumption and the amenity services of the forest, utility is derived from the bequest. In the first period the forest-owner perceives the possibilities of both consuming and bequeathing to the next generation, both of which are conditional on his survival probability. The model is structured in such a way that it lets the forest-owner bequeath all his assets that are left at the time he passes away, instead of *a priori* deciding on the level of bequests. This structure circumvents the conceptual question of what happens, at the occurrence of passing away, to those assets that were not planned to be bequeathed. That particular question was left unanswered in the models used in the earlier literature (e.g. Ollikainen 1998, Amacher et al. 1999) that formulated a specific decision defining the size of inheritance.

The comparative statics analysis is carried out to examine analytically the effects of ageing on consumption and harvesting, and also the effects of taxes on harvesting. The substitution and income effects of ageing and taxes are derived using the Slutsky decomposition. The numerical analysis demonstrates how consumption changes in the presence of taxes and how the effects of four taxes on harvesting vary among different age groups of forest-owners.

The results of article (**II**) indicate that the optimal consumption is linked to both taxation and the forest-owner's age. The effects of taxes are studied when taxation takes place both through consumption and through bequests. Consumption first decreases and then increases when moving from younger to older individuals regardless of whether non-timber assets are more or less heavily taxed through bequests rather than consumption. The former case typically corresponds to a situation in which inheritance takes place between distant relatives, whereas the latter corresponds to a situation where inheritance takes place between close relatives. The results also show that the effects of each specific tax are generally dependent on the forest-owner's age. Age tends to intensify the increasing effect on harvesting of the forest bequest tax. The same is true with respect to the decreasing effects on harvesting of the inheritance tax imposed on non-forest assets. Furthermore, the forest-owner's age tends to intensify the negative effect on harvesting of the capital income tax imposed on forest assets, but diminishes the negative effect on harvesting of the capital income tax imposed on non-forest assets. In this article the non-neutrality of the capital income tax on timber assets is linked to the perceived survival probability, and hence to the forest owner's age, rather than to the existence of inheritance taxes as in Amacher et al. (1999).

The comparative statics results show that in the case of the capital income taxes on forest and non-forest assets and also the inheritance tax on non-forest assets, the substitution effect works towards decreasing harvesting levels, whereas the income effect is ambiguous. The negative substitution effect always dominates in the numerical examples.

3.3 Impacts of carbon-based policy instruments and taxes on tropical deforestation

Article (**III**) uses a market equilibrium framework to investigate the demand for and supply of cleared tropical forestland, and to analyze the effects of carbon payments and taxes imposed on forestry and cash-crop sectors in combating tropical deforestation. The supply of cleared forest land is derived by using a two-period utility maximization model in which the carbon sequestration of private forestland holders is credited. Demand for cleared land is derived from the profit maximization model of a cash-crop farmer. On the supply side, the private forestland holders value forest amenities, but less than what is globally a desired level, because they do not fully value the global public goods. The supply side model treats the forests as a non-renewable resource. This enables one to capture the reality of tropics where tropical forest clearing is often more than a one-way traffic; once tropical forest is cleared, the cleared land ends up in other uses such as cash-crops. The model considers carbon payments under two systems where carbon-credited land can either be redeemed or not. The demand-side model includes a Cobb-Douglas-type production technology for cash-crop with three inputs: land, labor and an aggregate input composed of all material inputs apart from land and labor. The numerical analysis of the market equilibrium uses data from the humid Chaco eco-region of Paraguay, which is an important biodiversity region in South America.

The results of article (**III**) indicate that taxes on cash-crop and forestry incomes in fact can be an ineffective measure in curbing tropical forest clearing. On the other hand, the carbon payment would make the private forestland holder value the standing forests more and hence clear less forest. It is shown that in the context of the humid Chaco eco-region of Paraguay, at €30 per ton of carbon, the deforestation would be restricted to 10 percent of existing forest cover. The carbon payments would also incentivize the private forestland holder to be more responsive to land prices when making clearing decision. This, in turn, would increase the land price in cash-crop. A reversible carbon crediting system, where a forestland holder can redeem the credited forest from conservation to timber production, seems to substantially increase the effectiveness of carbon payments in the short run. The carbon payments could also complement the tax on cash-crop incomes in curbing tropical forest loss. Therefore, an effective policy to combat tropical deforestation should consider forestry and cash-crop sectors together. It is also shown that to bring 25 percent of the privately held forest under conservation in humid Chaco region of Paraguay, no taxes or carbon payments are needed. To conserve any share of forest exceeding 25 percent but less than or equal to 66 percent, a constant carbon payment of just over €25/tC is needed. To conserve beyond 66 percent, the required carbon payment rate increases with the increase of conservation share. As the conservation share grows, the market equilibrium land price increases, thus making it less attractive to cash-crop farmers. The required carbon payment rate is, however, very minimally affected by the presence of a forestry income tax.

3.4 On the economics of tropical deforestation: carbon credit markets and national policies

Article (**IV**) uses an infinite time horizon dynamic optimization model to study the economics of tropical deforestation under a carbon compensation scheme. Earlier analytical models investigating tropical deforestation (e.g. Walker and Smith 1993, Bulte and van Soest 1996, and Mateo 1997 Mendelsohn 1994, Amacher et al. 2009, Barbier et al. 2005, Hartwick et al. 2001), did not consider a carbon compensation scheme. The carbon compensation scheme provides the forestland owners with an alternative to deforestation: they can sell the forests on the international carbon credit markets. The model treats the tropical forests as a non-renewable resource, and combines forest amenity valuation into the decision framework with regards to non-renewable resources. The deforestation behavior of both private and public sectors are modeled. Both sectors maximize utility from consumption in addition to forest amenities over an infinite time horizon. The private agent is assumed to have a smaller weight on the amenity preferences compared to the social planner. The justification for this is that the social planner includes in his decision the amenity benefits accruing to a wider group of people than does the private agent. For example, deforestation within a community area may have adverse impacts on the farming conditions of a neighboring community, which are typically ignored by the private agents. Table 2 summarizes the methodologies used in article (**IV**) and other three articles of this thesis.

The model highlights the fact that carbon compensations would increase the value of a standing forest. The results suggest that the rate of land income tax needed to enforce a socially optimal tropical forest stock should equal the proportional difference between the social and private amenity valuations of tropical forests. The carbon compensation policy crucially depends on pre-existing land income taxation policy. The existence of such a taxation policy may require the government to pass the same rate of carbon compensation that it received from the international community to private forestland owners to ensure socially optimal tropical forest stock. Under a pre-existing sub-optimal land income taxation policy, it may be optimal for the government to either over-transfer or under-transfer the carbon compensation depending on the level of forest amenity valuation of private landowners. In the complete absence of a taxation policy, the government may always require to over-transfer the carbon compensation to the landowner. The results imply that an effective carbon compensation scheme such as under the REDD framework should take into consideration existing national policies such as the land income taxation that affects deforestation.

Table 2: Methodologies used in separate articles

Article	Model category	Forest amenity valuation with	Endogenous variable(s)	Analytical analysis	Numerical analysis	
					Data source	Program used
I	Two-period forestland	Amenity utility & intensity	Net saving, clear-cutting and thinning shares	Comparative statics	A representative Finnish NIPF owner's case	MATLAB
II	Two-period forestland	Amenity utility & intensity	Net saving, and clear-cutting share	Comparative statics	A representative Finnish NIPF owner's case	MATLAB
III	Two-period	Amenity utility but no amenity intensity	Forest clearing and carbon crediting shares, and current consumption	Optimal conditions, and land supply function	A representative private forestland holder's case in humid Chaco of Paraguay	MATLAB
	Cobb-Douglas-type	*No amenity valuation*	Cleared land and other input demands	Land demand function and market equilibrium	A hypothetical soy plantation case in humid Chaco eco-region of Paraguay	
IV	Infinite horizon dynamic optimization	Amenity utility but no amenity intensity	Forest clearing and carbon crediting shares, and consumption in each period	Optimal conditions and policy rules	*Numerical analysis not conducted*	

4. DISCUSSION AND CONCLUSIONS

4.1 Taxation effects, amenity preference and ageing of forest-owners

Article (**I**) of this thesis offers a number of important insights regarding the behavior of different groups of forest-owners that are separated by their preferences for forest amenities. The results indicate that profit tax and the land value tax affect the harvesting decisions of only those forest-owners whose preferences are relatively balanced between timber production and amenity values. These taxes are neutral to the harvesting decisions of the forest-owners who are relatively biased toward either timber production or amenity values of forest. This implies that forest-owners amenity values do not necessarily make the forest taxes non-neutral to the harvesting decisions of private forest-owners. It is rather the intensities of the preferences for forest amenities of the forest-owners that affect the non-neutrality of forest taxes concerning forest harvesting. Earlier studies (see Section 2.2.1) have only investigated the non-neutrality of certain forest taxes in the presence of the forest amenity valuation, without addressing the issue of how the forest taxation effects vary at different intensities of preferences of forest amenity values of the forest-owners.

The intensity of amenity preferences of the forest-owners is a key factor in determining whether or not a tax regime with a lowered profit tax and a land value tax brings Pareto-improvement to a regime with a higher profit tax but no land value tax. Furthermore, according to the results of article (**I**), the popularity of thinning to replace clear-cutting increases as the intensity of preferences for forest amenities produced by standing forest increases. This implies that thinning may be the preferred method of forest harvesting over clear-cutting in mature forests among those forest-owners who are relatively biased toward forest amenities values.

In article (**II**), the age of forest-owners affects their decisions between consumption and leaving bequests irrespective of taxes present. This implies that forest-owners' ageing is important in determining how taxes affect forest-owners' consumption and bequest decisionmaking. Earlier forest economics literature (see Section 2.2.2) had not discussed the issue of consumption and bequests in relation to forest-owners' ageing. The non-neutrality concerning forest harvesting in response to the capital income tax imposed on forest assets (which is equivalent to profit tax) also depends on forest-owner's age. Furthermore, article (**II**) shows that forest-owner's age intensifies the positive effect on harvesting of the inheritance tax on forest assets and the negative effects on harvesting of the capital income tax on forest assets and inheritance tax on non-forest assets, but age diminishes the negative effect on harvesting of capital income tax on non-forest assets.

4.2 Taxation effects and policy instruments that target climate services from forests

Article (**III**) shows that income taxes on forestry and cash-crops, on their own, may be ineffective in curbing tropical forest loss, whereas the carbon payments may be effective. A reason for the ineffectiveness of taxes could be that they target tropical forest loss only indirectly. Carbon payments complement taxes on forestry and cash-crop incomes in curbing tropical forest loss. This finding provides evidence in favor of the argument made by Karsenty (2010) that taxes alone may not be enough to ensure sustainable tropical forest management; instead they should be used as a component of a consistent set of actions and public policies for the best effect. Article (**III)** estimates the carbon payment rate needed to avoid forest loss in the humid Chaco eco-region of Paraguay (e.g. €30 per ton of carbon emission avoided would be sufficient to limit deforestation to 10 percent of existing forest cover in the area). Moreover, to bring 25 percent privately held tropical forest under conservation, no taxes or carbon payments are needed. This share coincides with Paraguayan regulations that require private forestland holders to retain 25 percent of their forest while clearing forests. To conserve any share of forest more than 25 percent but less than or equal to 66 percent, a constant carbon payment of just over €25/tC is needed. This is because at a carbon payment rate of €25/tC or, it is not optimal for the private landholder to participate the carbon crediting scheme, but once the rate just exceeds €25/tC, he finds it optimal to conserve maximum of 66 percent of his forest. To bring more than 66 percent forest under conservation, higher carbon payment rates are required as the conservation share grows. Moreover, the required rate of payment is affected only minimally by the presence of a forest income tax. The increasing trend of carbon payment rate may be linked to the fact that the opportunity costs of clearing forests increase as the conservation share grows (see also Kindermann 2008).

Article (**IV**) demonstrates the dependency of optimal carbon compensation policies of a national government on existing land income taxation. How much carbon compensation is optimal for a national government to pass onto forest-owners depends upon whether or not land income taxation exists in that particular country and, if so, on whether or not that taxation is optimally set. The joint effects of carbon compensation and taxation systems may make it optimal for a national government to use different carbon compensation rates than the standard rate it received from the international community when passing on compensations at local levels. Article (**IV**) also shows that the necessity of land income taxation to bring the private optimal level of tropical forest resource to social optimal level depends upon the levels of forest amenity valuations of the private and public sectors. As long as they differ, a tax is needed, but no tax is needed when they are identical. This suggests that the land income tax has effects similar to Pigouvian type of taxes.

4.3 Policy implications and conclusions

The results of the four articles included in this thesis have a number of policy implications. The interlinkages between forest tax effects and the intensity of forest amenity preferences (article **I**) suggest that forest-owners' general attitudes and objectives with respect to their forest ownership will have an impact on the effectiveness of forest taxation policies. For example, clear-cutting may be reduced whereas thinning harvests may increase as a result of tax policy measures. Since the effectiveness of tax policies depends upon the actual intensity and distribution of the amenity preferences among forest-owners, it might serve as an incentive to implement a tax regime that recognizes this. In one such regime forest-owners could voluntarily opt for a combination of an estate type of tax and timber sales tax, as an alternative to a sole timber sales tax. Forest-owners' amenity preferences would be an important factor in determining their choice between the tax regimes. The discussion indicates the importance of developing methods to measure forest-owners' amenity preferences quantitatively. Experimental or contingency methods could be used for such measurement. Investing in this line of research would help policy makers formulate more efficient policies for nonindustrial private forest-owners.

The dependency of the effects of capital income and inheritance taxes on forest-owner's ageing (article **II**) suggests that the design of taxation that targets the actors in the forestry sector should take into consideration the demographic profile of forest-owners and the likely development of this profile. The age-distribution of non-industrial private forest-owners in many countries is skewed towards the older generations, whose reactions to capital income and inheritance taxes may be fundamentally different from those of younger generations. The finding in article (**II**) that ageing affects the level of harvests of mature forest substantially implies that changes in the age-distribution of the forest-owners can affect the wealth distribution between forest and non-forest assets in society. On the other hand, as the inheritance tax on timber assets increases the current harvesting, it could effectively be used as a policy tool to ensure an increased timber supply in the short run.

In addition, the findings of articles (**I** & **II**) have implications from the point of view of achieving public policy goals concerning forest conservation in mitigating climate change. The results of article (**I**) indicate that when forest-owners have more balanced objectives between timber and forest amenities, the profit taxation works better in reducing harvest, which may lead to achieving more climate goals through forest conservation. Likewise, a general implication of the results of articles (**I** & **II**) is that taxation that targets the forestry sector should also be designed with a view to its links to the forest-owners' amenity preferences and its consequences for forest conservation. Moreover, as shown in article (**II**) both the capital income taxes and the inheritance tax on external assets work toward tying up more capital in the standing timber stock by decreasing the current harvesting. Consequently more timber is conserved voluntarily by the landowners compared with a case where these taxes on external assets are not in existence. Due to the presence of theses taxes, implementing forest conservation policies on private land and achieving targets, such as carbon sequestration, nature-based recreation, securing more old growth structure etc. may thus become less costly for governments. Moreover, a finding of the article (**I**) is that as the forest-owners become more biased toward amenity values of forests, thinning becomes more desirable over clear-cutting as the harvesting method. If this development takes place, it may lead to a shift toward continuous cover-type forestry and may thus ensure more biodiversity, carbon sequestration and environmental services from private forests.

According to article (**III**), the complementarity between the carbon payment and the tax measures in curbing deforestation suggests that the effective policies should target forestry and agricultural sectors in combination and policies for these sectors should be coordinated. The effectiveness of carbon-based policy instruments in combating tropical deforestation largely depends on the way avoided deforestation is compensated in the future, for example, under REDD regimes. Therefore, the value of tropical forests should be carefully considered when formulating policies. Moreover, as suggested in article (**III**) the carbon-based policy instruments such as carbon payments may lead to reducing tropical forest clearing. This may have two contrasting policy implications. First, if the development of policy that regulates climate services from forest sector is not uniform throughout a region or the world, the strict enforcement of such a policy in one country or region may lead to leakage, i.e. transferring forest loss to other countries or regions in which effective policies to protect tropical forest from being cleared do not exist or are not enforced strictly. Second, if the policy development is relatively uniform throughout a region, it may push plantation investment and development, and efficient use of wasteland to satisfy the increased timber and fiber demands. A uniform development of policy that regulates climate services from forests may also call for further technological innovation to enhance cash-crop or agricultural productivity as no more land from forest clearing would be allocated to cash-crop or agriculture.

In article (IV) it is shown that the carbon compensation policies of government of a tropical forest owning country crucially depend on pre-existing land income taxation in that country. The joint effect of the carbon compensation and land income taxation suggests that rather than using the compensation rate set by international community, it would be optimal for each national government to use its own set of flexible rates when compensating local forestland owners for not clearing forests. Therefore, a carbon compensation policy for saving tropical forests should take into account existing national policies such as taxation that affects deforestation. A more general implication of the results of article (IV) is that the carbon compensation scheme studied could be one possible way to set up international compensatory policies between developed and less developed countries as hypothesized in the REDD initiative of the UNFCC.

Based on the above discussion it can be concluded that agent specific factors such as ageing and individual amenity preferences should be considered in designing forest taxation policy. Moreover, existing policies such as land income taxation should be considered in designing carbon-based policy instruments to enhance the role of forests in climate change mitigation.

REFERENCES

Adams, D. M., Alig, R. J., McCarl, B. A., Callaway, J. M. and Winnett, S. M. 1999. Minimum cost strategies for sequestering carbon in forests. Land Economics. 75(3): 360-374.

Alix-Garcia, J. 2007. A spatial analysis of common property deforestation. Journal of Environmental Economics and Management. 53 (2): 141-157.

Alvarez, L. H. R. and Koskela, E. 2007. Taxation and rotation age under stochastic forest stand value. Journal of Environmental Economics and Management. 54: 113-127.

Amacher, G. 1997. The design of forest taxation: a synthesis with new directions. Silva Fennica. 31(1): 101-119.

--- and Brazee, R. J. 1997. Designing forest taxes with varying government preferences and budget targets. Journal of Environmental Economics and Management. 32: 323-340.

---, Rios, M., Constanino, L. and Brazee, R. J. 1998. The design of second best forest incentives in small open economies. Forest Science. 44(1): 165-175.

---, Brazee, R., Koskela, E., and Ollikainen, M. 1999. Taxation, bequests, short and long run timber supplies: an overlapping generation problem. Environmental and Resource Economics 13 (3):269-288.

---, E. Koskela, and Ollikainen, M. 2009. Deforestation and Land Use Under Insecure Property Rights. Environment and Development Economics. 14: 281-303.

---, Ollikainen, M. and Koskela, E. 2002. Optimal forest policies in an overlapping generations economy with timber and money bequests. Journal of Environmental Economics and Management. 44: 346-369.

---, Ollikainen, M. and Koskela, E. 2009. Economics of forest resources. The MIT Press, Cambridge, Massachussets, USA. 397 pp.

---, Ollikainen, M., Koskela, E. and Conway, C. 2003. Bequest intentions of forest landowners. theory and empirical evidence. American Journal of Agricultural Economics. 84 (4): 1103-1114.

Angelsen, A. 1999. Agricultural Expansion and Deforestation: Modeling the Impact of Population, Market Forces, and Property Rights. Journal of Development Economics 58, 85–218.

---. 2010. Policies for reduced deforestation and their impacts on agricultural production. PANS. 107 (46): 19639-19644.

--- and Kaimowitz, D. 1999. Rethinking the Causes of Deforestation: Lessons from Economic Models. World Bank Research Observer. 14: 73-98.

Anthon, S., Lund, J. F. and Helles, F. 2008. Targeting the poor: taxation of marketed forest products in developing countries. Journal of Forest Economics. 14: 197-224.

Asante, P., Armstrong, G. W. and Adamowicz, W. L. 2011. Carbon sequestration and the optimal forest harvest decision: A dynamic programming approach considering biomass and dead organic matter. Journal of Forest Economics. 17 (1): 3-17.

Barbier, E. B., and Burgess, J. C. 1997. The economics of tropical forest land use options. Land Econ 73(2):174-195.

---, R. Damania, and Leonard, D. 2005. Corruption, Trade and Resource Conversion. Journal of Environmental Economics and Management. 50: 276–299.

Binkley, S. C. 1980. Economic analysis of the allowable cut effects. Forest Science. 26 (4): 633-642.

Bowes, M.D. and Krutilla, J.V. 1985. Multiple use management of public forestlands. In Kneese, A.V. and Sweeney, J. L. (eds.). Handbook of natural resource and energy economics, vol. II Elsevier Science Publishers B. V. (North-Holland), Amsterdam. p. 531-569.

Bröner, J, and Wunder, S. 2008. Paying for avoided deforestation in the Brazilian Amazon: from cost assessment to scheme design. International Forestry Review. 10(3): 496-511.

Bulte, E. and van Soest, D.P. 1996. Tropical deforestation, timber concessions, and slash and burn agriculture- why encroachment may promote conservation of primary forests. Journal of Forest Economics 2: 55-66.

Butler, R. A., Koh, L. P. and Ghazoul, J. 2009. REDD in red: palm oil could undermine carbon payment schemes. Conservation Letters. 2 (1): 67-73.

Calish, S., Fight, R. D. and Teeguarden, D. E. 1978. How do non-timber values affect Douglas fir rotations? Journal of Forestry. 76(4):217-221.

Chang, S. J. 1982. An economic analysis of forest taxation's impact on optimal rotation age. Land Economics. 58: 310-323.

---. 1983. Rotation age, management intensity and the economic factors of timber productions: do the changes in stumpage prices, interest rate, regeneration costs and forest taxation matter? Forest Science. 29: 267-277.

Chladná, Z. 2007. Determination of optimal rotation period under stochastic wood and carbon prices. Forest Policy and Economics. 9: 1031-1045.

Conrad, R.F., Gillis, M. and Mercer, D.E. 2005. Tropical harvesting and taxation: a dynamic model of harvesting behavior under selective extraction systems. Environmental and Development Economics. 10:689-709.

Englin, J.E., and Klan, M. K. 1990. Optimal taxation: timber and externalities. Journal of Environmental Economics and Management. 18 (3):263-275.

--- and Callaway, J. M. 1993. Global climate change and optimal forest management. Natural Resource Modeling. 7(3): 191-202.

FAO. 2010. Global Forest Resource Assessment 2010. Rome, Italy.

Favada, I. M., Karppinen, H., Kuuluvainen, J., Mikkola, J. and Stavness, C. 2009. Effects of timber prices, ownership objectives, and owner characteristics on timber supply. Forest Science. 55(6):512–523.

---, Kuuluvainen, J., Uusivuori, J. 2007. Optimal timber stock in Finnish nonindustrial private forests. Forest Policy and Economics. 9(5):527-535.

Guthrie, G. A. and Kumareswaran, D. 2009. Carbon Subsidies, Taxes and Optimal Forest Management. Environmental and Resource Economics: 43:275-293.

Hardie, I., and Parks, P. 1997. Land Use with Heterogeneous Land Quality: An Application of an Area Base Model. American Journal of Agricultural Economics. 77: 299–310.
Hartman, R. 1976. The harvesting decisions when a standing forest has value. Economic Inquiry. 14: 52-58.
Hartwick, J., N. Van Long, and Tian, H. 2001. Deforestation and Development in a Small Open Economy. Journal of Environmental Economics and Management. 41:235–251.
Heaps, T. 1984. The forestry maximum principle. Journal of Economic Dynamic and Control. 7: 131-151.
Hoen, H. F. and Solberg, B. 1997. CO_2-taxing, timber rotations and market implications. Critical Review of Environmental Science and Technology. 27: 151-162.
Hultkranz, L. 1992. Forest Policy and Bequest Motive. Journal of Environmental Economics and Management. 22(2):164-177.
Hunt, C. 2008. Economy and Ecology of emerging markets and credits for bio-sequestered carbon on private land in tropical Australia. Ecological Economics. 66: 309-318.
Johansson, P.-O. and Löfgren, K.-G. 1985. The economics of forestry and natural resources. Basil Blackwell Inc. New York. 292 pp.
Kaimowitz, D. and Angelson, A. 1998. Economic Models of Deforestation: A Review. Center for International Forestry Research, Bogor, Indoensia.
Karsenty, A. 2010. Forest taxation regime for tropical forests: lessons from Central Africa. International Forestry Review. 12 (2): 121-129.
Keeler, A.G. 2005. Sequestration rental policies and price path of carbon. Climate Policy. 4:419-425.
Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S. and Beach, R. 2008. Global cost estimates of reducing carbon emissions through avoided deforestation. PNAS. 105 (30): 10302–10307.
Klemperer, W. D. 1976. Impacts of tax alternative on forest values and investments. Land Economics. 52: 135-157.
---. 1978. An analysis of forest tax equity guides. Forest Science. 24(3): 318-326.
Koskela, E. and Ollikainen, M. 1997. Optimal design of forest taxation with multiple-use characteristics of forest stands. Environmental and Resource Economics. 10: 41-62.
Koskela, E .1989a. Forest taxation and timber supply under price uncertainty: perfect capital markets. Forest Science. 35 (1):137-159.
---. 1989b. Forest taxation and timber supply under price uncertainty: credit rationing in capital markets. Forest Science. 35 (1):160-172.
--- and Ollikainen, M. 2001. Forest taxation and rotation age under private amenity valuation: New results. Journal of Environmental Economics and Management. 42: 374-384.
--- and Ollikainen, M. 2003. Optimal forest taxation under private and social amenity valuation. Forest Science. 49 (4): 596-607.
Kovenock, D. 1986. Property and income taxation in an economy with an Austrian sector. Land Economics. 62(2): 201-209.
Kuuluvainen, J. 1990. Virtual price approach to short-term timber supply under credit rationing. Journal of Environmental Economics and Management. 19: 109-126.
---, Karppinen, H., and Ovaskainen, V. 1996. Landowner objectives and nonindustrial private timber supply. Forest Science. 42 (3): 300-309.
Löfgren, K-G. 1991. Another reconciliation between economists and forestry experts: OLG-arguments. Environmental and Resource Economics. 1: 83-96.
--- and Johansson, P-O. 1982. Six different results on the properties on the timber supply function, Working Paper No 39, Swedish University of Agricultural Sciences.

Lomander, P. 1983. Optimal harvest policy under the influence of imperfections and uncertainty. Working Paper 22. College of Forestry, Department of Forest Economics, Umeå, Sweden. 77p.

Mateo, S. 1997. Are deforestation and capital accumulation processes related? An analytical model. Mimeo.

Max, W. and Lehman, D. E. 1988. A behavioral model of timber supply. Journal of Environmental Economics and Management. 15: 71-86.

Mendelsohn, R. 1994. Property rights and tropical deforestation. Oxford Economic Papers 46: 750-6.

Mitra, T. and Wan, H. 1985. Some theoretical results on the economics of forestry. Review of Economic Studies. LII: 263-282.

Murry , B. C. 2000. Carbon values, reforestation, and perverse incentives under the Kyoto Protocol: an empirical analysis. Mitigation and Adaptation Strategies for Global Change. 5 (3): 271-295.

Naidoo, R., Malcom, T. and Tomasek, A. 2009. Economic benefits of standing forests in highland areas of Borneo: quantifications and policy impacts. Conservation Letters. 2 (1): 35-44.

Namaalwa, J., Sankhayan, P. L. and Hofstad, O. 2007. A dynamic bio-economic model for analyzing deforestation and degradation: a approach to woodlands in Uganda. Forest Policy and Economics. 9: 479-495.

Ollikainen, M. 1990. Forest taxation and the timing of private nonindustrial forest harvests under interest rate uncertainty. Canadian Journal of Forest Research. 20: 1923-1929.

---. 1991. The effect of non-timber taxes on the harvest timing- the case of private non-industrial forest-owners: a note. Forest Science. 37(1):356-363.

---. 1993. A mean-variance approach to the short-term timber supply and forest taxation under multiple sources of uncertainty. Canadian Journal of Forest Research. 23: 573-581.

---. 1996. The analytics of timber supply and forest taxes under endogenous credit rationing- separability after all. Journal of Forest Economics. 2: 93-130.

---. 1998. Sustainable forestry: timber bequests, future generations and optimal tax policy. Environmental and Resource Economics. 12 (3): 255-273.

Ovaskainen, V. 1992. Forest Taxation, Timber Supply, and Economic Efficiency. Acta Forestalia Fennica 233. The Society of Forestry in Finland and the Finnish Forest Research Institute, Helsinki. 88 p.

---, Hänninen, H., Mikkola, J. and Lehtonen, E. 2006. Cost-sharing and private timber stand improvements: A two-step estimation approach. Forest Science. 52(1):44-54.

Parks, P. J., E. B. Barbier, and Burgess, J. C. 1998. The Economics of Forest Land Use in Temperate and tropical areas. Environmental and Resource Economics 11(3–4): 473–487.

Persson, M. U. and Azar, C. 2010. Preserving the world's tropical forests- a price on carbon may not do. Environmental Science and Technology. 44(1): 210-215.

Pfaff, A., Kerr, S., Lipper, L., Cavatassi, R., Davis, B., Hendy, J. and Sanchez-Azofeifa, G. A. 2007. Will buying tropical forest carbon benefit the poor? Evidence from Costa Rica. Land Use Policy. 24 (3):600-610.

Pohjola, J. and Valsta, L. 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Policy and Economics. 9: 789-798.

Romero, C., Ros, V. and Daz-Balteiro, L. 1998. Optimal forest rotation age when carbon captured is considered: theory and applications. Journal of the Operations Research Society. 49(2):121-131.

Ruzicka, I. 2010. Taxation of tropical forests: search for generalizations after half a century of trying. International Forestry Review. 12(2):181-186.

Salo, S. and Tahvonen, O. 2002a. On equilibrium cycles and normal forests in optimal harvesting of tree vintages. Journal of Environmental Economics and Management. 44(1): 1-22.

---. and Tahvonen, O. 2002b. On the optimality of a normal forest with multiple land classes. Forest Science. 47(3): 530-542.

---. and Tahvonen, O. 2003. On the economics of forest vintages. Journal of Economic Dynamics and Control. 27 (8): 1411-1435.

Samuelson, P. A. 1976. Economics of forestry in an evolving society. Economic Inquiry. 14: 466-492.

Sohngen, B and Brown, S. 2008. Entending timber rotations: carbon and cost implications. Climate Policy. 8: 435-451.

--- and Mendelsohn, R. 2003. An optimal control model of forest carbon sequestration. American Journal of Agricultural Economics. 85(2): 448-457.

Strang, W.J. 1983. On the optimal forest harvesting decision. Economic Inquiry. 21: 576-583.

Tahvonen, O. 1995. Net national emissions, CO_2 taxation and the role of forestry. Resou. Energy Economics. 17 (4): 307-315.

---. 1998. Bequests, credit rationing and in-situ values in the Faustmann-Pressler-Ohlin Forestry model. Scandinavian Journal of Economics. 100(4): 781-800.

---, Salo, S. and Kuuluvainen, J. 2001. Optimal forest rotation and land values under a borrowing constraint. Journal of Economic Dynamic and Control. 25: 1595-1627.

Thompson, M. P., Adams, D. and Sessions, J. 2009. Radiative forcing and the optimal rotation age. Ecological Economics. 68:2713-2720.

Uusivuori, J. 2000. Neutrality of forest income taxation and inheritable tax exemptions for timber capital. Forest Science. 46 (2): 219-228.

--- and Kuuluvainen, J. 2005. The harvesting decisions when a standing forest with multiple age-classes has value. American Journal of Agricultural Economics 87(1): 61-76.

--- and Kuuluvainen, J. 2008. Forest taxation in multiple-stand forestry with amenity preferences. Canadian Journal of Forest Research. 38(4):806-820.

--- and Laturi, J. 2007. Carbon rentals and silvicultural subsidies for private forests as climate policy instruments. Canadian Journal of Forest Research. 37:2541-2551.

Valsta, L. 2007. Sequester or Harvest – the Optimal use of managed forests to mitigate climate change. Research Report No. 46. Department of Forest Economics. University of Helsinki. 23 p.

Varian, H. 1992. Microeconomic Analysis. 3rd edition. W.W. Norton & Company, New York, London.

von Kooten, G.C., Binkley, C.S. and Delcourt, G. 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. American Journal of Agricultural Economics. 77 (2): 365-374.

Walker, R.T. and Smith, T.E. 1993, Tropical deforestation and forest management under the system of concession logging: a decision theoretic analysis. Journal of Regional Science 33: 387-419.

Wibe, S. and Gong, P. 2010. Can forests save the world? Journal of Forest Economics. 16 (3): 177-178.