UNIVERSITY OF OSLO

DOCTORAL THESIS

Seven essays on policies and international cooperation to abate emissions of greenhouse gases

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Contents

List of essays

Essay 1
Renegotiation-Proof Climate Agreements with Full Participation: Conditions for Pareto-Efficiency
Joint work with Geir B. Asheim
Published in *Environmental and Resource Economics*

Essay 2
International emissions trading in a noncooperative climate policy game
Joint work with Dag Einar Sommervoll
Extended version of article published in *Economics Letters* (B. Holtsmark & Sommervoll, 2012)

Essay 3
Permit Trading: Merely an Efficiency-Neutral Redistribution away from Climate-Change Victims?
Joint work with Odd Godal
Published in *Scandinavian Journal of Economics*

Essay 4
Harvesting in boreal forests and the biofuel carbon debt
Published in *Climatic Change*

Essay 5
Quantifying the global warming potential of CO_2-emissions from wood fuels
Published in *GCB Bioenergy*

Essay 6
A comparison of the global warming effects of wood fuels and fossil fuels taking albedo into account
Sligthly revised version of paper published in *GCB Bioenergy* (B. Holtsmark, 2015a)

Essay 7
Faustmann and the Climate
Joint work with Michael Hoel and Katinka Holtsmark
Published in *Journal of Forest Economics*

Preface

The thesis consists of seven essays on climate policy and international environmental agreements. All essays have been written after I returned to the Research Department at Statistics Norway in 2002. I am grateful for the opportunity given by my employer to do research on environmental and resource issues.

Environmental issues have been an interest of mine since I was a schoolboy back in the 1970s and I became aware of the book "Limits to growth". I was also much influenced by "Thinking about the future" (a critique of the first mentioned book), which my father gave me.

Four of the essays of the thesis are joint work with some very bright and kind individuals. It has been a privilege for me to cooperate with all of you.

The first essay is a joint work with Geir B. Asheim. Working with Geir was intense and I learned a lot from this cooperation. To keep up with Geir's progress and irregular working hours, I in periods had to work really long days and nights irrespective of weekends and holidays.

Dag Einar Sommervoll gave important contributions to the second essay, especially the proof of its main result. With his keen sense of humor in addition to his mathematical skills, it was a pleasure to work with Dag Einar.

Also Odd Godal has a keen sense of humor. The third essay, with its beautifully clear result, was the outcome of hard work and many discussions between us. Odd lives in Bergen and we therefore almost never saw each other. This was compensated for by phone talks that sometimes went off track and ended up with discussions related to other important questions of life. We became close friends during the work with this essay.

The last essay is a joint work with Michael Hoel and my daughter Katinka Holtsmark. I have known Michael since I was his research assistant in a project related to the European gas market in the 1980s. Our paths have crossed several times since then. Michael has at all occasions supported me and made me believe in my ideas and skills. Over the years we have made several articles together, both for newspapers, magazines and journals. Michael's creativity and enthusiasm combined with his always scientific, open-minded approach have been a great inspiration.

It was also very fruitful to have my daughter involved in the work with the last essay. She solved quickly some mathematical challenges that I did disentangle and became impressively soon an important person in the author team.

Although I had a head start of 28 years, Katinka caught me up and submitted her thesis before me. Her extremely high productivity during her pregnancy impressed me and the submission of her thesis inspired me to submit my own after all these years.

With regard to the last four essays, I am grateful to Trygve Refsdal, who back in February 2010 contacted me and urged me to analyze the climatic consequences of bioenergy from forests. Shortly after, I was downright hooked trying to understand and model the fascinating dynamics of forests. At the first stage of this work, I also received important inputs from Ketil Flugsrud, Rasmus Astrup, Lise Dalsgaard, Hans Goksøyr and Olav Norem.

Communicating my research on bioenergy has meant many controversies with other researchers, policy makers, and representatives from the bioenergy business. This was not fun. Without support and encouragement from good colleagues, friends and family who believed in my ideas, I would definitely have given up this project. I will especially thank my father who passed away last year, my brother Sven Holtsmark, Hans Henrik Ramm, Trond Amundsen, Jørgen Randers, Taran Fæhn, Bente Halvorsen, Per Arild Garnåsjordet, and Iulie Aslaksen

Last, but not least, I am grateful for the life-long support from the wonderful woman in my life, Margit, who I was so fortunate to meet back in the 1970s, when we both were active in the environmental movement.

Later Margit gave me Katinka, Ole Kristian and Yngve. Their independent choices, hard work and impressive achievements have been of great inspiration to me.

Oslo, June 20, 2015.

Bjart Holtsmark

1. Introduction and summary[*]

The thesis consists of seven essays dealing with policies to mitigate climate change. The first three essays analyze aspects of international cooperation to abate emissions. More specifically, the first essay studies the design of a compliance mechanism when there is an international agreement on emission cuts. The next two essays analyze the effects of an international agreement with emissions trading, assuming that the national emission quotas are not results of an efficient international bargaining process, but instead are determined individually by national governments. The last four essays study how management of forests and use of wood-based bioenergy influence the accumulation of CO_2 in the atmosphere, and how forest management should be adjusted when accumulation of CO_2 in the atmosphere is considered to be socially damaging.

The thesis applies different methods. While the first three essays on international climate cooperation apply microeconomic theory and game theory, the last four essays on forest management combine basic microeconomic theory with life-cycle assessments, building on biological knowledge on the dynamics of forests and the interaction of the carbon stocks.

1.1. Background

Svante Arrhenius (1896) was the first scientist to estimate the global warming effect of an increasing concentration of CO_2 in the atmosphere. Arrhenius was aware that combustion of fossil fuels has the potential to increase the atmospheric CO_2 concentration and thus cause global warming. However, with the relatively low global emissions in the 19th century, it was not primarily global warming and climate change that was Arrhenius' concern. The foremost motivation for Arrhenius' work was to provide insights into the mechanisms behind the variations in global temperature during the Earth's geological history.

Global CO_2-emissions were relatively low also throughout the first half of the 20th century. However, following the Second World War the combination of a rapidly increasing world population and strong economic growth in many regions caused the use of fossil fuels to increase rapidly and CO_2-emissions to increase correspondingly. The emission growth has been especially high throughout the most recent decades. Roughly one third of all historical emissions of CO_2 has occurred since the turn of the millennium and emissions are likely to continue rising in the decades to come (World Energy Outlook 2014, International Energy

[*] I gratefully acknowledge valuable comments to a draft from Mads Greaker, Kjetil Telle, and Åsmund Sunde Valseth.

Outlook 2014) . This has resulted in concerns that the subsequent growing concentration of CO_2 and other greenhouse gases (GHGs) in the atmosphere is causing global warming and harmful climate change (IPCC, 2014b).

Many countries have implemented policies to limit their emissions of GHGs. Moreover, for more than two decades there have been international negotiations within the Framework Convention on Climate Change (UNFCCC, 1992). This convention does not specify any quantified and legally binding emission reduction commitments. Such commitments were included in the Kyoto Protocol (UNFCCC, 1997), although the national quotas specified were too generous to mean significant emission cuts (Böhringer, 2002; Hagem & Holtsmark, 2004). As only developed countries had emission limitations, the first commitment period of the Kyoto Protocol regulated less than 30 per cent of global emissions, and the agreement on the second commitment period put limits on even fewer countries and a correspondingly smaller share of global emissions. Moreover, negotiations for an effective, comprehensive international climate agreement to follow on from the Kyoto Protocol have shown little progress. Therefore, it appears to be an important task to study how international negotiations and agreements could be more effective. This is the main motivation for the first three essays of the thesis.

While the first three essays study international cooperation on emission abatement, the last four essays study one type of abatement policy, namely the use of bioenergy as an alternative to fossil fuels. Recent reports show that there are researchers with optimistic views on the potential role of bioenergy in global energy supply and as a tool to mitigate climate change, while others are more pessimistic and emphasize that there are also many environmental concerns related to increasing use of bioenergy, see for example Haberl, Erb, et al. (2013), IPCC (2011), and IPCC (2014a).

I will at this point add that also my research on bioenergy partly has its origin in the slow progress in the international climate cooperation. From my work on international cooperation, I found it unlikely that an effective, global climate agreement will be implemented and also other reasons why it appears likely that global GHG-emissions will be high over large parts of the 21st century (B. Holtsmark, 2006, 2013b; B. Holtsmark & Alfsen, 2005; Røgeberg, Andresen, & Holtsmark, 2010). This means that the limits for the CO_2-concentration considered as dangerous most likely will be exceeded within this century. From this perspective, there is a need for measures that will give results in this century and not measures that will enhance the CO_2-concentration within this time scale. When I after some preliminary work found reasons to believe that large-scale increased use of bioenergy from forests is likely to *increase*, not reduce, the CO_2-concentration over the entire 21st century, I found this worth further investigation.

Before I introduce the essays further, I will emphasize that this thesis does not enter into the discussion of to what extent there are reasons for alarm with regard to human influence on climate change. That discussion is beyond the scope of the thesis. Rather, the starting point for the essays is that policies to reduce GHG emissions have been and will be implemented in many countries. Hence, it is important to study the effects and costs of implemented and proposed policy measures. Moreover, as there have actually been international climate negotiations for decades, and these are likely to continue, it is valuable to provide insights into the effects of proposed agreement designs. Note also that the four essays on bioenergy and forest management have relevance to international climate negotiations, as the questions of climate neutrality of biomass and land use change are important in these negotiations.

1.2. The tragedy of the commons

The starting point for the thesis is that the atmosphere is a global commons, into which we discharge our industrial CO_2 and other GHGs. The approach worked for a long time, but according to IPCC (2014b) the system is evidently straining under the load. The more GHGs in the atmosphere, the greater the adverse impacts on the Earth's climate (IPCC, 2014b). At the same time each individual or country will have weak incentives to reduce their own emissions while the potentially dangerous amounts of GHGs accumulate in the atmosphere.

Garrett Hardin picturesquely described the problem studied in his article "The Tragedy of the Commons" in *Science* in 1968. Hardin drew and expanded on a story given in an 1833 lecture by William Forster Lloyd, then professor of political economy at Oxford.[1] The story is that several cattle-owners are allowed to let as many cows as they like graze a common open pasture, and do so without encountering problems. The capacity of the land is limited, however, and as the populations grow a point will inevitably be reached when "the inherent logic of the commons remorselessly generate(s) [a] tragedy" (Hardin, 1968, p. p. 1244).

The question each cattle-owner has to ask is "What is there to be gained from adding an extra cow to my herd?" The positive component comes from the sale of the additional quantities of beef, milk and hides provided by the additional cow. The negative component is

[1] As Copeland and Taylor (2009) noted, Hardin primarily popularized and raised awareness of the problems of resource management. He did not provide a complete analysis of the problems arising from free access to a resource.

the added pressure on the land, causing the productivity of the owner's original livestock to decline. The "tragedy of the commons" follows from the failure of each individual cattle-herder to take into account the effect on the productivity of all the other farmers' livestock. Without proper cooperation between the cattle-owners, the result is likely to be overgrazing and a general loss of welfare.

As Harding puts it, "Each man is locked into a system that compels him to increase his herd without limit – in a world that is limited." The basic purpose of the thesis is to be a contribution to the accumulation of knowledge on how society can escape from such traps.

1.3. Weak incentives to reduce emissions of greenhouse gases – numerical examples

Just as the cattle owners have strong incentives to increase their herd, countries have weak incentives to reduce their emissions of GHGs. Table 1 illustrates this. The table shows estimated reduction in global warming in 2025, 2050 and 2100 resulting from individual emission cuts by the world's three greatest countries, joint cuts by the group of developed countries, and joint cuts by the whole world, respectively. The temperature reductions caused by emission cuts are calculated using an impulse response function (IRF) derived from the carbon cycle model Bern 2.5CC (Joos & Bruno, 1996; Joos et al., 1996; Joos et al., 2001). This IRF was selected in the IPCC Fourth Assessment Report (IPCC, 2007) as their preferred model and is also applied in the fifth and sixth essays of this thesis. The applied model implies a climate sensitivity of 3 °C.[2] The numerical examples of Table 1 are based on model simulations described in B. Holtsmark (2013b). In the reference scenario the global temperature is approximately 2.3 and 4.2 °C higher in 2050 and 2100, respectively, compared to pre-industrial temperatures.

It is perhaps obvious that small countries have modest incentives to reduce domestic emissions. However, Table 1 illustrates that large countries, as the USA and China, also have weak incentives to cut domestic emissions. Moreover, the table shows that even the entire group of industrialized countries acting collectively together with China, will not achieve very much unless the rest of the world joins in.

For example, the third column in Table 1 shows a case where China follows a path implying extensive emissions cuts of 15, 65 and 95 per cent compared to the business-as-

[2] According to IPCC (2007, p. p. 38) "the climate sensitivity of carbon dioxide is usually defined as the equilibrium global average surface warming following a doubling of CO_2 concentration." Moreover, "climate sensitivity [of CO_2] is likely to be in the range of 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C." IPCC (2013) did not provide a best estimate of the climate sensitivity of CO_2.

usual (BAU) levels in 2025, 2050 and 2100, respectively. The numbers in this column isolate the temperature effect of China's emission reductions. The result would be a relatively modest slowdown in global warming; 0.01 °C, 0.07 °C, and 0.23 °C lower global temperature in 2025, 2050 and 2100 than in BAU, respectively. The corresponding numbers are similar or smaller for India and the USA, see the two subsequent columns of Table 1.

These numerical examples suggest that a single country's efforts, even over a very long period, will have a relatively small impact on global temperature change, also when the biggest countries of the world are considered. One should keep in mind that emission cuts of the size considered in Table 1 are costly, at least politically, to implement. Such emission cuts will, for example, require high taxes or other instruments that will have significant effects on end-user prices on energy. With weak climatic effects, as illustrated in Table 1, it could be difficult to have political acceptance for such policies. It follows that a joint effort by all or most countries in the world is likely to make more sense to the public and policymakers in the respective countries. This emphasizes the importance of knowledge on how international agreements should be designed, which is the topic of the first three essays of the thesis.

*Table 1. The slowdown in global warming when China, India or the USA unilaterally cuts emissions and if all developed countries or the whole world do the same.**

	Emission reductions from BAU*	Temperature change compared to no action °C				
		China	India	USA	All developed countries	Global action
2025	-15 %	-0.01 °C	-0.002 °C	-0.01 °C	-0.02 °C	-0.04 °C
2050	-65 %	-0.07 °C	-0.03 °C	-0.06 °C	-0.12 °C	-0.36 °C
2100	-95 %	-0.23 °C	-0.12 °C	-0.16 °C	-0.30 °C	-1.56 °C

*In the assumed BAU scenario China's CO_2 emissions are set to rise from 5.8 $GtCO_2$ in 2010 to 11.0 $GtCO_2$ in 2100. By assumption India's and the US BAU emissions will rise from 1.6 to 5.5 $GtCO_2$ and from 6.0 to 7.0 $GtCO_2$ over the period, respectively.

Source: B. Holtsmark (2013b)

1.4. Stable agreements and participation

It follows from the numerical examples in Table 1 that joint efforts by a significant group of countries, i.e. an international climate agreement, might be necessary to gain public support for large emission cuts on a global scale. At the same time, there are significant potential gains from freeriding on an ambitious agreement implemented by other countries. Free-riding occurs when a party receives the benefits of a public good without contributing to the costs (Nordhaus, 2015, p. p 1339). The question then is how agreements could be designed to overcome the incentives to free ride. At this point one should distinguish between *participation* and *compliance,* although these concepts cannot be analyzed in isolation to each other. The incentives to *participate* in an international environmental agreement is in the literature often analyzed by the use of non-cooperative game theory as originally conceived by d'Aspremont, Jaquemin, Gabszewicz, and Weymark (1983) in their study of cartels, see also Finus (2008) for an overview of related literature. The cartel-based concept leads to relatively pessimistic results on the prospects of the climate negotiations, which I will return to below. However, it should here be mentioned that another approach, taken by Chander and Tulkens (1995), see also for example Chander (2007), who find that the grand coalition is an equilibrium.

A coalition is defined as internally stable if each coalition member is better off as member of the coalition than as an outsider.[3] Using this concept in a model with quadratic abatement cost functions and linear climate damage functions, Barrett (1994) found that a coalition of more than three countries would be unstable, see also Hoel (1992). Before turning to a discussion of the compliance problem, an introduction to this frequently cited result is appropriate. This also serves as an introduction to the models applied in the first and the second essays. Moreover, the third essay contains a numerical example that applies a similar linear-quadratic model.

Consider a world with a set N of n identical countries. Denote the abatement in country i as q_i. Emission reduction is a public good; in other words, each country benefits from the overall emission reduction. Assume a linear relationship between global emission abatement and each country's benefits, expressed by $b\Sigma_i q_i$, where b is a positive parameter. The benefits of emission abatement are less damage from drought, warmer weather and so forth, and lower costs of adaptation to impacts, such as a rising sea level. Assume that the abatement cost function is quadratic.[4] If country i is to cut its emissions by q_i units, the cost is given by $(c/2)(q_i)^2$, where c is a positive parameter.

[3] The literature distinguishes between *internal* and *external* stability (Carraro & Siniscalco, 1993). A coalition is *internally* stable if no signatory would be better off leaving the coalition, while a coalition is *externally* stable if no outsider would be better off joining the coalition. I will in the following focus on internal stability, and for simplicity use the term *stability* for short.

[4] This is a frequently used functional form in the literature; see for example Barrett (1994) and Barrett (2003).

In the analysis below, the results are not influenced by the values chosen for b and c. To simplify, I therefore assume that $b = c = 1$. The payoff for country i then is:

$$v_i = \Sigma_{j\in N} q_j - ½ (q_i)^2, i = 1,2, \ldots, n. \quad (1)$$

Maximizing v_i with respect to q_i gives the abatement level $q^1 = 1$. Hence, if each country sticks to this abatement level, there is a Nash equilibrium in the sense that no player has anything to gain by changing his own strategy. If all countries choose the abatement level $q^P = n$, the joint welfare is maximized. Note that $q^P > q^1$.

Let us now assume that k of the n countries agree to reduce their emissions by k units each. An abatement level k is chosen because it level will maximize the joint welfare of the coalition countries. The remaining (n-k) countries, the outsiders, stick to the Nash equilibrium abatement level $q^1 = 1$, as this maximizes their individual payoffs.

Let v_{sk} be the payoff to a signatory to the agreement when there are k coalition members. From equation (1), we obtain that

$$v_{sk} = k^2 + (n-k) - ½ k^2. \quad (2)$$

Next, assume that one country withdraws from the agreement. The k-1 remaining signatories will maximize their joint welfare if they adjust their agreed abatement level to k-1, while the withdrawn country will choose its dominant strategy, which is abatement level $q^1 = 1$. Let v_{nk} be the payoff to an outsider. After withdrawal from an agreement with k parties, the payoff to the new outsider will be given by

$$v_{nk-1} = (k-1)^2 + (n-(k-1)) - ½. \quad (3)$$

From (2) and (3) we can obtain the gain from participation:

$$v_{sk} - v_{nk-1} = ½(k-1)(3-k). \quad (4)$$

It follows that without any agreement in the first place ($k = 1$), two countries will increase their payoffs if they come together and agree to increase their abatement level to $q^2 = 2$. If a third country joins the coalition, it will neither lose nor gain. However, as the expression in (4) is negative if $k > 3$, an outsider will lose by joining the coalition if it already includes least three signatories. Moreover, if an agreement includes four parties or more, a signatory will benefit from withdrawal (Barrett, 1994).

With regard to intuition to equation (4), one key factor is that the larger is a coalition, the deeper emission cuts will maximize the coalition's joint welfare. Thus, the larger is a coalition, the greater are the avoided abatement costs to a free-rider.

A reasonable question is how far the result that follows from equation (4) can be generalized. As I have pointed out, the values of parameters *b* and *c* do not affect the result.[5] On the other hand, other functional forms might lead to different results.

Of greater importance is probably the lack of dynamics in this type of games. Battaglini and Harstad (2015), Harstad (2012), Harstad (2015) apply dynamic models and are therefore able to include many strategic aspects of the formation of climate agreements that are neglected in the static games described above. It is therefore noteworthy that they find equilibriums with much larger coalitions.

There are also other reasons to be more optimistic than the result above indicates. Some studies have found that with heterogeneous countries and side payments, stable coalitions could be larger and agree on deeper emission cuts. For example, McGinty (2007) found that a stable coalition of 20 different signatories can result in 47 per cent of the difference between the full and no-cooperative solution, compared with 5 per cent for 20 identical nations. Furthermore, 72 per cent of the global payoff difference is obtained, relative to 9 per cent for identical countries. B. Holtsmark (2013b, p. p 340) reported similar results.

1.5. From participation to compliance – introduction and summary of the first essay

The game used to analyze the participation problem in the previous section assumes that if an agreement is reached, the signatories comply with their commitments to cut emissions. The question then arises how the agreement should be designed to actually provide incentives to comply. This is the topic of the first essay. Note here that despite the participation and incentive problems described above, the first essay assumes that the global community, or at least a group of countries, actually *is* able to come together and agree on emission cuts.

Compliance mechanisms cannot be discussed within a one shot game, where punishment could never be carried out. The first essay therefore introduces a repeated game in the sense that the countries interact in periods 0, 1, 2, ….. In each period the countries' payoffs are described by equation (1). Moreover, if there is an agreement among *k* countries to maximize their joint welfare, the coalition members' undiscounted payoffs in each period are described by equation (2).

[5] If we do not assign numerical values to *b* and *c*, equation (7) will read as follows: $v_{sk} = v_{nk-1} + ½b^2(k-1)(3-k)/c$. Hence, the gain resulting from participation is equal to $½b^2(k-1)(3-k)/c$. This expression is non-negative if $1 \leq k \leq 3$. A coalition of more than three countries will therefore be unstable irrespective of the size of *b* and *c*, provided they are positive, see Barrett (2005) and Hoel (1992).

However, within the model introduced in the previous section, and without any additional incentives, compliance will not pay off and the signatories are best off if they deviate and choose the Nash-equilibrium's abatement level $q^1 = 1$. Barrett (1999) therefore analyzed whether compliance would pay off if all complying signatories punish a deviating country by reducing their abatement level to $q^1 = 1$ in the period after the deviation. Assuming that all the n countries have joined the coalition, a country that deviates and abates $q^1 = 1$ in period 0, would then collect the following discounted payoffs in period 0 and 1:

$$v(0,1)_{defection} = [(n-1)n + 1 - ½] + \delta\, [n + (n - 1) - ½\, n^2], \tag{5}$$

where δ is the discount factor. The discount factor is defined as $\delta \coloneqq 1/(1+r)$, where r is the discount rate. With compliance, payoff would be:

$$v(0,1)_{compliance} = (1 + \delta)\, [n^2 - ½\, n^2]. \tag{6}$$

It follows that $v(0,1)_{defection} < v(0,1)_{compliance}$ if, and only if, $r < 1$. In other words, the punishment rule will make compliance pay off.

However, as Barrett (1999) found, this does not help very much if there are many signatories. They will all gain by renegotiating back to cooperation without imposing the punishment, thereby undermining the credibility of the punishment. Recall that if the punishment is carried out, the punishing countries' undiscounted payoffs in period 1 will be

$$n + (n - 1) - ½. \tag{7}$$

However, instead of carrying out the punishment, they could ask for renegotiation and propose that all signatories immediately return to the abatement level $q^n = n$. That would give the period 1 payoff:

$$n^2 - n^2/2. \tag{8}$$

It follows that renegotiation gives a strictly higher payoff if $n \geq 4$. Taking into account that also the deviating country will be better off with renegotiation, it follows that with at least four signatories they will all be strictly better off with renegotiation. Thus, the punishment threat is not credible. And Barrett (1999) and (Barrett, 2002) concluded that there is a trade-off between "narrow but deep" and "broad but shallow" agreements: credible punishment rules could only be designed if either only a few countries participate, or many countries participate with small emission cuts.

Two questions then arise. First, could the described credibility problem be overcome with a different punishment rule? Second, could a different punishment rule overcome the trade-off between depth and broadness found by Barrett?

The first of these two questions was analyzed by Froyn and Hovi (2008). Within the binary abatement choice model of Barrett (1999), and building on the approach taken by Asheim, Froyn, Hovi, and Menz (2006), they found that the credibility problem could be overcome if *only a subset of the signatories within a global treaty punishes a deviating country in the next period*. Froyn and Hovi (2008) found that a credible compliance rule could be constructed along these lines even in a global agreement. [6]

However, the binary abatement choice model applied by Asheim et al. (2006) and Froyn and Hovi (2008) makes the simplifying assumption that countries either abate one emissions unit or do not cut emissions at all. This type of model does not take into account that governments in reality could choose abatement levels along an almost continuous scale and, furthermore, that marginal abatement costs usually are increasing along this scale. This means that the abatement level (the depth of cooperation) that maximizes the joint welfare of a coalition of countries is increasing in the number of participating countries.[7] For example, considering the linear-quadratic model introduced in the previous section, the abatement level that maximizes the joint welfare of a coalition is proportional to the number of signatories. This important benefit from international environmental agreements is, for example, lost when the binary model is applied.

Due to the limitations of the binary choice model, it is important to check whether the results of Asheim et al. (2006) and Froyn and Hovi (2008) carry over to the models with continuous and strictly convex abatement cost functions. Moreover, the binary choice model, with a fixed depth of cooperation, cannot be used to analyze the second question raised above; whether a different punishment rule could overcome the problem that a broad treaty has to be shallow. Essay 1, which is a joint work with Geir B. Asheim, studies these questions. Moreover, the use of the continuous choice model allows for more detailed analysis of how credible punishment rules could be designed. The essay has been published in *Environmental and Resource Economics* (Asheim & Holtsmark, 2009).

The first essay finds, as its main result, that an efficient, broad and deep treaty can always be implemented as a weakly renegotiation-proof equilibrium, as defined by Farrell and

[6] Other types of enforcement mechanisms are analysed in the literature, for example trade sanctions, see Barrett (2008), Nordhaus (2015) or Hovi, Greaker, Hagem, and Holtsmark (2012), among others.
[7] If the countries have differently shaped abatement cost functions and different benefit functions, the depth of cooperation also depends on which countries participate.

Maskin (1989), if the discount rate is sufficiently low. As in Froyn and Hovi (2008), the solution is a compliance rule saying that only a *subgroup* of the complying signatories should punish the deviator, while the remaining signatories should stick to the agreed abatement level. The point here is that if the discount rate is sufficiently low, the rule then could be designed such that the punishing countries never will be willing to renegotiate, because they benefit from the abatement carried out by the complying countries that are supposed to stick to the Pareto-efficient abatement level.

For example, in the four-country-case, after a deviation in period t only two of the complying countries should reduce their abatement level in period $t+1$, while the third of the complying countries should stick to the Pareto-efficient abatement level. If the discount rate is sufficiently low, compliance will then pay off while the punishing countries are not willing to renegotiate.

The first essay includes an additional result showing how the depth of cooperation must be reduced for high discount rates. To stick to the four-country-example; the result means that if the discount rate is above approximately 0.44, then the Pareto-efficient abatement level could no longer be achieved as a weakly renegotiation-proof equilibrium. Figure 1 in the first essay shows how the abatement level has to be reduced as the assumed discount rate is increased. Note here that discount rates above 0.44 cannot be ruled out, as the period length considered is not necessarily one year, but more likely longer. Recall that the relevant length of the time period is determined by different factors, not least the time lag between a deviation and implementation of punishments. Punishments cannot be carried out before emission accounts are reported and properly reviewed, and so forth. Hence, the relevant time period is likely to be a number of years.

After the publication of the first essay in *Environmental and Resource Economics* in 2009, some papers have followed up the analysis. Heitzig, Lessmann, and Zou (2011) constructed a model with some similar features and propose other compliance mechanisms that will make compliance pay off and avoid renegotiation. Kratzsch, Sieg, and Stegemann (2012) point to the fact that Asheim et al. (2006), Asheim and Holtsmark (2009), and Froyn and Hovi (2008) consider *emissions* as the damaging factor. Kratzsch et al. (2012) improve the binary abatement choice model by taking into account that the accumulated *stock* of pollutants in the atmosphere is the relevant damaging factor, see also Hoel and Karp (2002) and Hoel and Karp (2001). Kratzsch et al. (2012) therefore analyzed renegotiation proof equilibriums and found that the results of Froyn and Hovi (2008) carry over to a binary choice model with a stock pollutant. It remains to show that their results considering a stock pollutant carry over to a continuous abatement choice model.

1.6. Permit trading without efficient bargaining of quotas – introduction to the second and third essays

Section 1.4 and the first essay studied situations where cooperating countries bargain efficiently in the sense that they agree on a set of national emission quotas that maximizes the signatories' joint welfare. This is a common approach in the literature on international environmental agreement.

The approach of the second and third essays is different and less optimistic and are contributions to a smaller literature that has its origin in Helm (2003). This literature studies cooperation when national quotas result solely from strategic national interests, not efficient bargaining. This approach has its motivation both in the pessimistic results in some of the contributions to the mentioned literature on international environmental agreements and in the development of international climate cooperation over the last decades. Indeed, there are as mentioned some recent contributions that give reasons to be more optimistic (Battaglini & Harstad, 2015; Harstad, 2012, 2015). However, both the simple participation game introduced in section 1.4 and the numerical examples presented in section 1.3 emphasize the difficulties related to international climate cooperation. Moreover, the international climate talks have resulted in little agreement other than the Kyoto Protocol. It is, as mentioned, usually concluded that the aggregate target of the countries that ratified the treaty and made a quantified commitment, is not substantially different from the signatories' aggregate business as usual emissions; see, e.g., Springer (2003) for a survey. Hence, although well furnished with good intentions, international climate talks this far have resulted in few outcomes that resemble efficient bargaining and collective behavior.

The relevance of the chosen approach taken in the second and third essays could be illustrated by the Copenhagen Accord, the agreement reached at the 15th Conference of the parties to the Climate Convention in Copenhagen in 2009 (UNFCCC, 2009). The Accord envisages emission cuts. However, the sizes of the national quotas were not specified after negotiations at the meeting. Instead, the Accord concluded that the signatories should individually quantify their national quotas *after* the meeting and submit these emission targets to the secretariat of the Climate Convention without any further bargaining (UNFCCC, 2009, p. § 4).

Despite the described lack of efficient bargaining in determination of national emission quotas, emissions trading has retained its key position in the climate talks. For example, the Copenhagen Accord, §4, states that commitments could be carried out jointly, which means that the agreement allows emissions trading. The reason is obviously the efficiency arguments for international emissions trading. When the initial allocation of permits is considered as already given and fixed, these arguments are well established. Quite simply, voluntary exchange cannot harm any trading party but is likely to give efficiency gains. Moreover, this policy instrument has further been identified as a promising tool when the initial allocation is not already given, but rather is part of the problem. The reason is that it can serve as a vehicle to facilitate side payments in international negotiations. Such payments have the potential to broaden international participation and deepen the emissions cuts.

The question, however, is whether these promising aspects of emissions trading apply in a world with less efficient bargaining. The purpose of the second and third essays of this thesis is to examine some possible consequences of emissions trading in a fairly fragmented world where governments struggle to maximize their collective objectives. The underlying assumption is that decisions are better reflected by governments optimizing on individual concerns along the lines considered in the studies by Helm (2003) and Carbone, Helm, and Rutherford (2009). In this type of setting, governments that decide to take on quantified international commitments, select their quotas individually without any bargaining with other governments. Still, the governments recognize each other's emission permits as transferable documents.

What could such a setting deliver in terms of overall efficiency and emission cuts? To address this question, the second and third essays, for purpose of comparison, also consider the classical case (labeled *policy A*), where governments decide individually and voluntarily on their national emission levels while emissions trading does not take place. If we abstract from problems of carbon leakage, the marginal domestic abatement cost then becomes equal to the aggregate national marginal benefits of emission abatement.

There are two sources of inefficiency associated with policy A. First, due to the weak incentives for individual emissions reductions discussed above, global emissions are too large. Second, when abatement levels are such that marginal domestic abatement costs become equal to the aggregate national marginal benefits of emission abatement, abatement efforts are inefficiently allocated because damages from climate change caused by GHG emissions will vary between countries.[8] To eradicate the latter cause of inefficiency, one could combine an international emissions trading system (called *policy B*) with policy A. Indeed, if countries' original endowments of emission allowances (targets, for short) were fixed at the emissions levels of policy A, trading (policy B) would yield efficiency gains, to no countries' disadvantage.

The key point of the second and third essays is that trade (policy B) creates incentives that are absent under policy A alone. The establishment of an international permit market creates prospects of revenues for national economies by export of emission allowances. Therefore, the second and third essays consider cases where the emission targets are not fixed at the levels of policy A, but instead are influenced by governments' anticipation of emissions trading with potential revenues.

The second essay is limited to an analysis of the combination of policies A and B. The third essay goes a step further and takes into account that fossil-fuel taxes and subsidies (*policy C*) are in widespread use (IEA, 2014; OECD, 2013). The effective price of carbon is determined not only by the permit price, but also by such taxes and subsidies. In similar lines as discussed in Hoel (1993, p. p 224), the third essay addresses that an international agreement could *change* the involved governments' design of their fossil fuels tax policy, see also Ederington (2001) for a similar discussion related to trade agreements. The contribution of the third essay is to combine domestic emission taxes and subsidies, policy C, with policies A and B. This is then compared to a situation without emissions trading, i.e. a combination of policies A and C only.

1.7. Effects of emissions trading – summary of the second essay

The second essay is a joint work with Dag Einar Sommervoll and is an extended version of an article published in *Economics Letters* (B. Holtsmark & Sommervoll, 2012).[9]

The model introduced by Helm (2003) is the starting point for the second essay. He studied a combination of policy A and B.

In contrast to the models applied in section 1.4 and in the first essay, the second essay considers at set of heterogeneous countries in the sense that both abatement cost functions and benefits from abatement vary between countries. Define countries that experience high and low damages from climate change as H-countries and L-countries, respectively. H-countries

[8] I here abstract from another source of efficiency of this case discussed in (Hoel, 2005); that countries choose carbon taxes that are differentiated across sectors. The purpose is to reduce leakage, i.e. influence emissions in other countries.

[9] The proof of the main result in B. Holtsmark and Sommervoll (2012) is compact. This is made more accessible in the second essay. In other respects, the second essay is identical to B. Holtsmark and Sommervoll (2012).

will experience high benefits from abatement, i.e. have a large b_i, while L-countries will experience low benefits from abatement, have a small b_j, where *i* and *j* are country indexes. With policy A alone, type H countries will impose ambitious emission cuts in the sense that marginal abatement costs become large. Correspondingly, L-countries will impose less ambitious targets.

With emissions trading (policy B), marginal abatement costs become equalized between countries and in the case with linear benefits from abatement, the permit price will be equal to the average of the countries' marginal benefits (B. Holtsmark & Sommervoll, 2009, p. p. 11) . This means that H-countries will carry out less abatement with trade, while L-countries will abate more. This redistribution of abatement efforts represents an efficiency gain.

However, whether trade leads to increased efficiency or not depends on the countries' adjustments of their targets when trade is introduced. Type L countries choose less ambitious targets when trade is introduced. Conversely, type H countries choose more ambitious targets (Helm, 2003). The total effect on global emissions in the model of Helm (2003) becomes ambiguous. This also applies to efficiency.

With policy A alone, global emissions are inefficiently high. Hence, if trade (policy B) leads to less abatement overall and even more inefficiently high emissions, this draws in the direction of reduced efficiency. This efficiency loss might outweigh the efficiency gains from trade. Because it is not clear whether trade leads to more or less abatement globally, it is unclear whether trade gives an efficiency gain.

The second essay extends the climate policy game of Helm (2003). In the second essay each country comprises a government and a set of identical firms. The number of firms varies between countries. Emissions stem from the firms, and they have all the same quadratic abatement cost function. It follows that each country's aggregate abatement cost function is quadratic as well.

As the first essay, the second essay assumes that the countries experience linear benefits from global emission abatement. However, now the marginal benefits from global emission abatement vary and are proportional to the number of firms in the country. This assumption reflects that the size of the benefits from abatement (avoided damages from GHG emissions) is likely to be related to the size of the economies.

The firms and the governments participate in a two-stage game. In stage 1 each government chooses an emission target, its pre-trade endowments of emission allowances. The allowances are transferred to the firms. In the second stage, all firms have access to an international permit marked while being committed to keep their emissions equal to or below their respective after-trade stock of emission permits. While the firms are price-takers, the governments take into consideration that the chosen sizes of the emission targets influence the global permit price.

In equilibrium the global permit price becomes equal to the average marginal benefits from abatement. It follows that large economies will carry out less abatement as trade is introduced, and become permit importers. Small economies will increase their abatement and become permit exporters (see also Proposition 1 in Helm, 2003).

As small countries by definition have fewer firms than larger countries, smaller countries have a steeper aggregate marginal abatement cost function than larger countries. Consequently, a large economy must typically make a greater downward adjustment of its abatement level than a typical small economy adjusts its abatement upwards. This is the basic mechanism leading to the second essay's first main result, which is that less abatement will be carried out with trade.

In addition, the first essay finds that also efficiency is reduced with trade. On the one hand, trade gives an efficiency gain due to efficient cross-border allocation of abatement. On the other hand, increased emissions from an inefficiently high level represents an efficiency loss. The essay finds that the latter effect dominates.

Section 1.9 provides a discussion related to this result.

1.8. Emissions trading combined with taxes and subsidies – summary of the third essay

The third essay is a joint work with Odd Godal, and was published in *Scandinavian Journal of Economics* (Godal & Holtsmark, 2011).

As in the second essay, the point of departure of the third essay is the classical case (policy A) where governments decide voluntarily on their emission levels without subsequent trade. Also the third essay combines policy A with an international emissions trading system (policy B). The contribution of the third essay is to introduce domestic emission taxes and subsidies and combine this (policy C) with policy A and B.

The motivation for inclusion of taxes and subsidies is their widespread use. For example, in India fossil fuel consumption subsidies in 2010 amounted to more than 1 per cent of GDP, while in Russia fossil fuel subsidies were close to 3 per cent of GDP in the same year (IEA 2011, p. 516). Subsidies are also significant in China. It has been estimated that if fossil fuel subsidies where completely phased out by 2020, global energy demand would be cut by nearly 5 per cent and CO_2-emissions by 5.8 per cent (IEA, 2011, p. p. 507). Moreover, fossil fuel taxes are also in widespread use, especially in developed countries (OECD, 2013, p. p. 12). It might be unrealistic to assume that these taxes and subsidies are fixed and independent of the countries' commitments in an international climate agreement. Therefore, the third essay analyzes how an agreement will influence the governments' incentives for setting of their subsidies and taxes on fossil fuels.

The third essay applies a less restrictive model than the second essay, as it does not adopt the model with a set of identical firms. Neither is there a restriction that the damage functions are linear. Rather, the more general formulations of the national abatement cost and damage functions of Helm (2003) are adopted. The contribution in relation to Helm (2003) is to introduce taxes and subsidies, and this turns out to have substantial effects on the solution of the game.

The main result is that when determination of the sizes of taxes and subsidies becomes part of the game, i.e. that policy A and B are combined with policy C, then the resulting profile of emissions is identical to that of policy A alone. This means that the possibility to adjust taxes and subsidies will totally undo any potential efficiency gains and emission cuts from international emissions trading, even though the permit market flourishes.

There are, however, distributional consequences of combining policy C with A and B. Countries with low domestic marginal damage costs of emissions will have lower emissions than targets; they become permit exporters. Conversely, countries with a high domestic marginal damage cost become permit importers. Because the allocation of abatement between countries is exactly as with policy A alone, this means that the introduction of trade inflicts an additional cost on countries with high damage costs from emissions, while countries with smaller costs from emissions will collect a gain from trade.

1.9. Interpretation of results of the second and third essays and closely related research

Both the second and the third essay have clear results although they do not point in the same direction. While the second essay finds detrimental effects of emissions trading, the third essay finds that emissions trading neither causes efficiency gains nor losses, but leads to the allocation of emission abatement that would take place without any trade. Although these conclusions differ, they both question whether emissions trading will always provide the efficiency gains usually expected.

It is here important to emphasize that there are other contributions that point in others directions. Not least important in that respect is the contribution by Carbone et al. (2009). They applied a computable general equilibrium model of the world economy and found that a system of internationally tradable emission permits could enhance global abatement significantly. This is in contrast to the results of both the second and third essays. How could this be explained? First, note that B. Holtsmark and Sommervoll (2009, p. p.12) found that in the type of game analyzed in Carbone et al. (2009), emissions trading leads to increased emissions if there is a negative covariance between the countries' marginal benefits from abatement and the steepness of their marginal abatement cost curves. Within the setting of the second essay, the marginal benefit of abatement is proportional to the countries' number of firms, while the steepness of the countries' marginal abatement costs curves is decreasing with the number of firms. Hence, within the model of the second essay, it follows that emissions trading will give increased emissions.

In contrast, Carbone et al. (2009) did not include any such restrictions on the relationship between the sizes of the countries and the benefits from emissions reductions. Instead, they argue that Japan and the USA, and especially Europe, will experience high benefits from abatement, while the former Soviet Union and China will experience much smaller benefits from abatement. With these assumptions together with equilibrium effects, they find promising benefits from emissions trading also in the non-cooperative setting. This emphasizes that too strong conclusions should not be drawn from the results of essays 2 and 3, although they point to some important mechanisms.

Since the second and third essays were published in 2012 and 2011, some other closely related contributions have been published.

Greaker and Hagem (2014) apply the non-cooperative approach to emissions trading introduced by Helm (2003). In addition they include in the model the effects of investments in research and development in emission abatement technologies. Their main result is that permit trading changes the strategic effects of technology investments and that emissions trading could make it desirable for industrialized countries to overinvest in technology both at home and in developing countries.

A more closely related paper is the recent contribution by Helm and Pichler (2015) who also apply the non-cooperative choices of permit endowments of Helm (2003). However, their attention is mainly on how subsidies for technology transfers influence the results, not on the effects of emissions trading. They find that subsidizing technology transfers leads to the adoption of better abatement technologies, thereby reducing international permit prices, and they find that the subsidies therefore tend to reduce countries' non-cooperative choices of endowments and thus reduce overall emissions. Moreover, they find that trading gives governments incentives to subsidize technology transfers and that trading through this mechanism gives lower overall emissions also in a non-cooperative environment. In other words, subsidies leads to improved technologies, which make emission abatement cheaper.

K. Holtsmark and Midttømme (2015) provide another recent contribution closely related to the second and third essays. They consider a game where the countries issue emission allowances non-cooperatively. They change the model by construction of a dynamic game. Moreover, they include endogenously determined investments in a clean technology. In this setting they find that there are gains from trade even when countries are identical. The mechanism is that the emissions trading option turns permits into an intertemporal strategic component. They find that if one country issues fewer permits today, other countries will respond by issuing fewer permits in the future. The reason is that fewer permits today increases current investments in green technology in all involved countries and countries will respond by issuing fewer emission allowances in the future. Hence, they find that emissions trading in the non-cooperative environment, which also is the starting point for the second and third essays of this thesis, will give reduced emissions and higher efficiency, in contrast to the results of the second essay.

The contrasting results in the research contributions described above show that there is uncertainty with respect to the effects of emissions trading in a world with limited international cooperation. With the central position of emissions trading in international climate cooperation, further research on this issue would be valuable.

1.10. Climate impacts of bioenergy from boreal forests

The vast boreal forest belt plays a crucial role in the Earth's carbon cycle. It covers large parts of Alaska, Canada, Scandinavia and Russia and stores approximately twice as much carbon as the tropical forest region and approximately as much carbon as the entire atmosphere (Kasischke, 2000). The last four essays of the thesis deal with the management of these forests from a global climate perspective and the question of whether there are climate benefits from increased use of wood-based bioenergy from these forests.

Although the starting point for my research on this issue has been the Norwegian forest and Norwegian forest policy, the findings of all four essays have a broader application with relevance to the entire boreal forest belt, which stretches over the northern hemisphere in a large circumpolar band covering large areas of Alaska, Canada, Scandinavia, and Russia.

The boreal region's climate is cold with a long winter season. The trees grow correspondingly slowly. Coniferous trees are the dominant plant form.

The boreal forests are important from other perspectives than climate, not least for recreation and with respect to biodiversity. The boreal forests are the home of some of the last intact terrestrial and aquatic ecosystems and large and diverse populations of mammals and birds.

At the same time many boreal forest areas have considerable potential for increased supply of bioenergy through boosted harvesting. For example, in Norway the current harvesting level is approximately at 30 – 40 per cent of a sustainable harvesting level (NEA 2010).[10] Therefore, the Norwegian government, as part of the national climate policy, seeks to increase the harvesting level and have implemented different subsidies and other policies to achieve this target (NMAF, 2008). Also in Sweden there is a considerable potential for increased supply of wood-based bioenergy even though the Swedish forests already, due to significant subsidies, supply approximately 100 TWh bioenergy annually (Kullander, Frank, Hedberg, Lundin, & Rachlew, 2015).

The basic question dealt with in the last four essays is whether increasing the harvesting level in the boreal forests for energy purposes will provide climate benefits or whether it could amplify climate change. The approach is interdisciplinary, taking advantage of knowledge and methods from biology, life cycle analysis and economics.

An important starting point for the analysis is that combustion of wood emits approximately as much CO_2 per unit of energy output as coal, and more if the moisture content of the wood is high, see Searchinger et al. (2009) and Hohle (2001). At the same time CO_2-emissions from combustion of biomass have traditionally been considered to be "carbon neutral", i.e. not part of the climate problem. Consequently, emissions from combustion of bioenergy should not be reported to the Kyoto Protocol and is not at the expense of the national quota.[11] For the same reason, to my knowledge, no country with carbon taxes imposes the tax on CO_2-emissions from bioenergy. Moreover, firms included in emissions trading markets are not committed to acquiring and surrendering allowances for emissions

[10] A *sustainable harvesting level* is defined as a harvesting level that could be sustained in the long term while the volume of standing wood converts to a stable level.

[11] The Kyoto Protocol, the only international climate agreement with quantified emissions reduction commitment, does not give Norway any credits for more than 1.5 MtCO2/year that is captured by forest (Höhne, Wartmann, Herold, & Freibauer, 2007). Because the annual carbon capture even in the high harvesting scenario is higher than 15 $MtCO_2$/year in any case, and emissions from combustion of bioenergy should not be reported, the Kyoto Protocol gives Norway strong incentives to increase the harvesting irrespective of its net effect on emissions.

from the combustion of bioenergy. This is also the case in the European market for emissions permits, which includes Norway.

With sustainable forest management, the harvest of one crop is replaced by the growth of a new crop. This growth reabsorbs the amount of carbon that was released by burning the first crop. It is therefore argued that combustion of biomass should not be considered as a source for global warming or climate change, i.e. 'carbon-neutral' or 'climate neutral'.

This is, to some extent, a reasonable argument in the case of crop-based biofuels when new crops within one or a few years replace those that are harvested, at least if one ignores the emissions that are generated by converting native habitats to cropland, an issue that has been analyzed in several studies, see for example Fargione, Hill, Tilman, Polasky, and Hawthorne (2008), Gibbs et al. (2010), Lapola et al. (2010), and Melillo et al. (2009). There is, however, a basic difference between bioenergy based on such rapidly growing crops and bioenergy based on wood from boreal forests. The regrowth of a typical boreal spruce or pine tree takes 70 – 120 years, and when considered mature and ready for harvest, the trees are usually still growing and still serve as carbon sinks (Storaunet & Rolstad, 2002).

Despite these well known facts, it has been common to consider wood as a carbon-neutral energy source also in scientific literature dealing with possible climate benefits from bioenergy, see for example Bright and Strømman (2009), Petersen and Solberg (2005), Raymer (2006), Sjølie, Trømborg, Solberg, and Bolkesjø (2010), and Zhang et al. (2010). These studies include thorough summing of all emissions associated with logging and processing of wood for fuel production. And they make careful track of emission reductions achieved when the considered amounts of bioenergy are assumed to replace fossil fuels. When they come to the emissions of CO_2 from the combustion of wood, however, these are simply not accounted for, due to the view that those emissions are carbon neutral. I will in the following argue that conclusions with regard to the effect of bioenergy on the net accumulation of CO_2 in the atmosphere become misleading with that approach.

It should here be noted that Tahvonen (1995) was an early contribution that did not accept the carbon neutrality assumption, but rather argued that also CO_2 emissions from combustion of bioenergy should be part of CO_2-tax regimes. More recently, a large literature has emerged showing the inadequacy of the carbon neutrality assumption related to wood-based bioenergy, see for example Chum et al. (2011), Friedland and Gillingham (2010), Haberl (2013), Haberl et al. (2012), Haberl, Schulze, et al. (2013), B. Holtsmark (2012), Hudiburg, Law, Wirth, and Luyssaert (2011), Schulze, Körner, Law, Haberl, and Luyssaert (2012), Searchinger et al. (2009), McDermott, Howarth, and Lutz (2015).

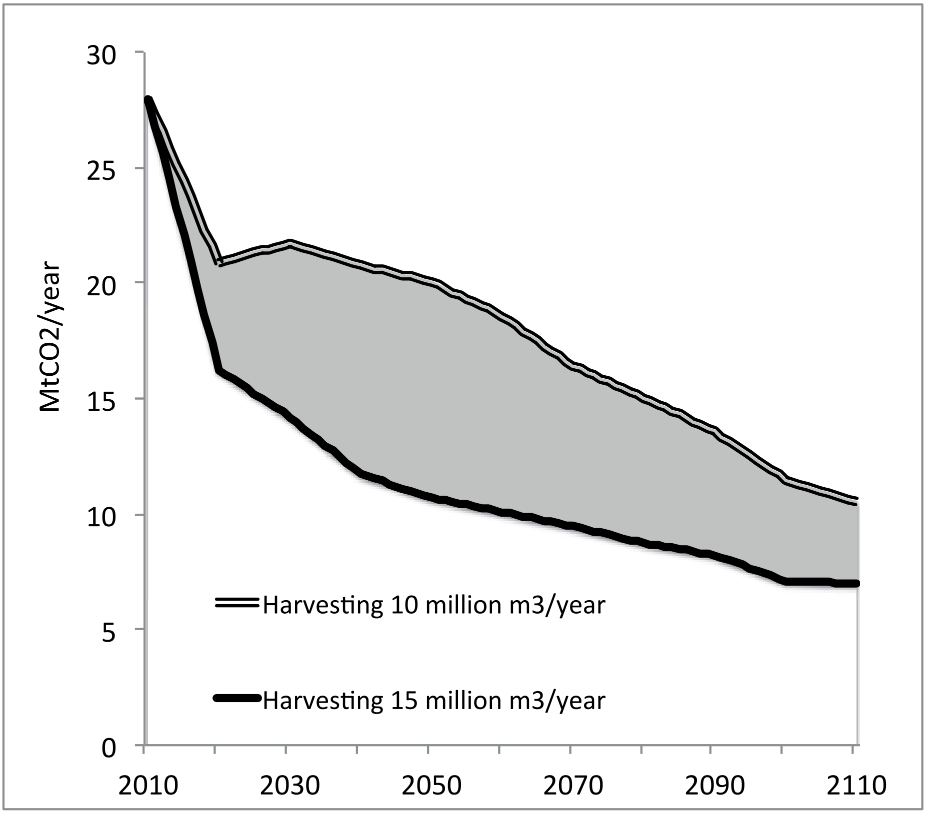

Figure 1. Annual net carbon capture in the Norwegian forest in two harvesting scenarios according to model simulations carried out at the Norwegian Forest and Landscape Institute (the NFLI-model).
Source: NEA (2010)

To illustrate the inadequacy of the carbon neutrality assumption related to bioenergy from forests, it is useful to draw attention to a report from the Norwegian Environment Agency (NEA, 2010). This report considered two harvest scenarios for the Norwegian forest for the period 2010 - 2110; one reference scenario with an annual harvesting at the current level of approximately 10 mill m^3 and a scenario in which the harvesting level is increased to 15 million m^3, which is the harvesting level defined as a goal by the Norwegian Government (NMAF, 2008). The scenarios were constructed by simulations with a model of the Norwegian forest constructed at the Norwegian forest and landscape institute (in the following labeled the NFLI-model). Figure 17.2 in NEA (2010), which is reproduced as Figure 1 below, shows that in both scenarios the forest's carbon stock is growing during the entire simulation period.[12] With regard to the question of carbon neutrality, it is noteworthy that the Norwegian forest's net annual uptake is likely to be 5 – 9 $MtCO_2$ higher in the low harvesting scenario compared to the high harvesting scenario (Figure 1).

From the figures reported in NEA (2010), it follows that over the considered simulation period of 100 years, the reduction in the forest's net uptake of CO_2, due to increased harvesting, would accumulate to approximately 650 million tonnes (the grey area of Figure 1). NEA (2011, pp. Figure 3-5) reported similar results and did also show that the result would be similar also if extensive silvicultural measures were taken.

NEA (2010) also reports the potential amount of fossil fuels that could be replaced by certain amounts for wood-based energy. According to NEA (2010, p 186), one m^3 wood could provide energy to replace fossil fuels used for heating that would have caused 0.7 – 1.0 tonnes of fossil CO_2 emissions. If instead one m^3 wood is used as raw material for production of second generation liquid biofuel and replaces petrol, it could eliminate 0.2 – 0.3 tonnes of fossil CO_2 emissions, according to NEA (2010).[13]

A simple arithmetic exercise then provides an important result: The increased harvesting level would over the considered 100 years period give 500 million m^3 of wood that could be used for energy purposes. According to the figures from NEA (2010) listed above, this amount of wood could over the entire simulation period replace an amount of fossil fuels that would have caused emissions of 100 – 500 $MtCO_2$. Relating these figures to the estimated drop in the forest's carbon stock of 650 $MtCO_2$, means that increasing the annual harvesting to the proposed level, will lead to *increased* accumulated net emissions over the 100 years simulation period of 150 – 550 $MtCO_2$ even when it is taken into account that increased supply of bioenergy replaces fossil fuel consumption.

Although NEA (2010) and NEA (2011) provided the foundation for this numerical example, which indicates that increasing use of wood-based bioenergy will mean more CO_2 in the atmosphere over the entire 21st century, those reports did not include similar numerical exercises and seem instead to take for granted that bioenergy from increasing the harvesting level is advantageous from a climate perspective.[14] Indeed, as I will demonstrate below, bioenergy also from boreal forests could provide climate benefits in the very long term.

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[12] The two scenarios reported in NEA (2010) were based on simulations with the numerical model developed at the Norwegian Forest and Landscape Institute (NFLI). NEA (2010) also considered a third scenario, but that scenario was not based on model simulations and will therefore not be analysed here.

[13] The figures in NEA (2010) had an increase of 3 millions m^3 wood as the starting point. The numbers presented here are scaled down to correspond to a single m^3 instead.

[14] For example, the project leader for Klimakur stated that "the total climatic impact [of increased extraction of wood] will be positive when one includes the effects in the long term" (Økstad, 2010).

However, the reports did not give any information on how far into the future there will be climate benefits from the Norwegian government's bioenergy policy. This and other unsolved questions were the starting points for my research, which led to the last four essays of this thesis. The research questions considered in these essays could be summarized as follows:

1. Will a different dynamic model of the Norwegian forest confirm that a higher harvesting level is going to have such a significant negative effect on the forest's carbon stock that was found by the NFLI model studies?
2. The NFLI model has a time horizon limited to 100 years. It is therefore an open question what are the very long term effects on the forest's carbon stock of increasing the harvesting level. To make a model with a wider time horizon was therefore a second task.
3. When wood fuels should no longer be considered carbon neutral, the question comes up how to quantify the climate impact of such fuels. The fifth and sixth essays apply the concept *global warming potentials* (GWP) to provide answers to such questions.
4. Fargione et al. (2008) introduced the concept "biofuel carbon debt", which is applied in the fourth and sixth essays. However, Fargione et al. (2008) did not study wood-based biofuels. It was therefore an open question whether the concept has relevance for wood-based biofuels. And if so, what is the length of the payback time?
5. After clear-cutting a stand, the snow surface during the winter season will to a large extent reflect sunlight (increased albedo). This has a cooling effect. How does this influence the net warming effect of harvesting?
6. The German forester Martin Faustmann published in 1849 a study with a rule for optimal time of harvesting (Faustmann, 1849). The last essay discusses how Faustmann's rule should be adjusted when there is a social cost of CO_2 emissions.

1.11. Introduction to the fourth essay

In the following, I will introduce the fourth essay of this thesis ("Harvesting in boreal forests and the biofuel carbon debt", published in *Climatic Change*). As some methods applied in the essay were applied in the last three essays of the thesis as well, the introduction to the fourth essay will be somewhat more comprehensive than the introduction and summary of the last three essays.

The fourth essay is based on simulations with a model of the Norwegian forest. The purpose for construction of this model, which will be called the H-model, was two-fold. First, the model simulation results presented in NEA (2010, 2011), which were based on the NFLI-model, had a 90 - 100 years time horizon and were too short to show the long term climate benefits that are assumed to be the final result (Økstad, 2010). Hence, an important task appeared to be to construct tools that could calculate the very long-term effects of wood-based bioenergy. Moreover, other scientific contributions to the discussion of climate effects of bioenergy usually have had time horizons of several centuries, see for example Fargione et al. (2008) where the time horizon is more than 800 years. A model with a wider time horizon would therefore be useful. Second, construction of a new model that is not based on the methods applied in construction of NFLI-model, would be a useful test on the reliability of the simulation results presented in NEA (2010, 2011).

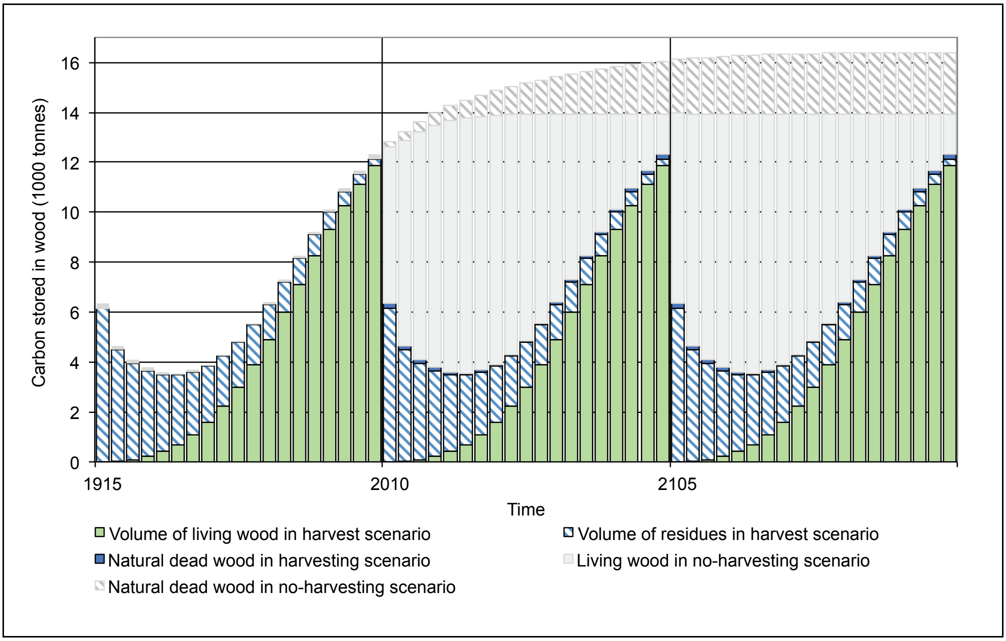

Figure 2. The dynamics of the carbon stock of a single stand, the basic building block of the H-model of the Norwegian forest. The colorized columns in the front show the development of the carbon stock in the harvest scenario. The considered stand was mature and harvested in 1915, 2010, 2105, 2200, and so forth. The grey columns in the background show the stand's carbon stock in the no-harvesting-scenario, i.e. no harvesting in 2010 or later.

Source: B. Holtsmark (2012)

As the productive part of the Norwegian forest covers an area of approximately 75 000 km^2, the H-model consists of 75 000 stands, each covering an area of one km^2. To make the model as transparent as possible, it was assumed that all stands have identical dynamic properties with regard to growth of living biomass and accumulation of dead organic matter. However, the time since the last clear-cutting varies and the distribution of the stands' ages is calibrated to fit data on the age distribution of the Norwegian forest provided by Larsson and Hylen (2007).

Essential for the dynamics of the H-model is that immediately after clear-cutting has taken place, the parcel's volume of living biomass drops to zero, and thereafter, the growth path begins again, see Figure 2. The volume of living biomass in a single parcel depends solely on the parcel's stand age. The parcel's productivity is fairly normal for a boreal forest and is close to the growth path of Norway spruce with productivity class 14 defined by Braastad (1975).

After clear-cutting, a share of the harvesting residues is left on the parcel. The stock of residues decomposes gradually, as illustrated in Figure 2. The accumulation of natural dead wood in each parcel of forest after clear-cutting and replanting is also shown in Figure 2.

In a boreal forest, in contrast to a tropical rain forest, a large share of the carbon is stored in the soil. According to Kjønaas et al. (2000), more than 80% of carbon in Norwegian forests is stored in the soil. An important question is therefore whether harvest is likely to trigger the release of carbon from soil. Such effects were not included in the H-model applied in the fourth essay. Effects on soil carbon, were, however, included in the models applied in the fifth and sixth essays, but did not turn out to be important for the results. The degree of uncertainty with respect to effects on soil carbon of harvesting is, however, significant, as discussed in the fourth essay.

1.12. Main results of the fourth essay and some additional simulation results

The findings of the fourth essay are based on simulations with the H-model described briefly above. Further details are given in the appendix to this essay.

Before giving a summary of the fourth essay, it should be noted that simulations with the H-model basically confirmed the findings of the NFLI-simulations reported in NEA (2010, 2011). However, the simulations with the H-model found a somewhat smaller drop in the forest's carbon stock over the 21st century if the harvesting level is increased to 15 Mm^3, see Figure 3. This difference is partly due to the inclusion of soil carbon dynamics in the NFLI-model, while effects on soil carbon is, as mentioned, not included in the H-model.

The H-model was simulated several hundred years into the future. In these simulations the forest's carbon stock stabilizes at a lower level in the high harvesting scenario compared to the scenario that sticks to the current harvesting level, see Figure 3. Hence, not even in the long term bioenergy is carbon neutral.[15]

Figure 2 provides the very simple explanation to this result. This diagram shows that the carbon stock of a stand at any point in time is greater in the non-harvesting case than in the harvesting case. In the high harvesting scenario an increased share of the stands follow the harvesting path instead of the no-harvesting path. It follows that the carbon stock of the forest also in the long term will be greatest in the low-harvesting scenario.

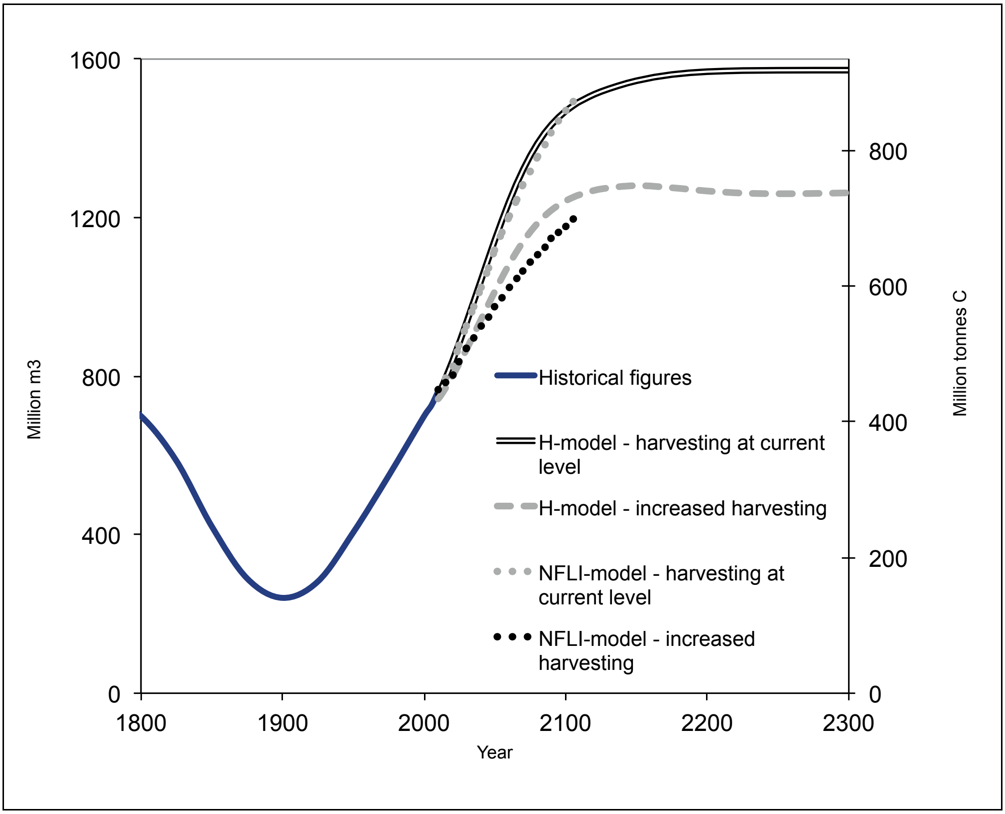

Figure 3. The stock of wood in the Norwegian forest, historically and in model simulations with both the H-model and the NFLI model.

Source: Norwegian Forest and Landscape Institute (historical figures), NEA (2011) and Statistics Norway.

It could here be argued that clear-cutting a stand is an opportunity to replace sparse or unproductive trees with more productive trees. The simulations shown in Figures 2 and 3 do not take that into account. The appendix to the fourth essay therefore includes a scenario that

[15] B. Holtsmark (2013a) discusses this in further detail and presents model simulations for the next 1000 years.

assumes that after clear-cutting and replanting, the density of the trees in all harvested stands is 25 per cent higher than the density of the standard parcel as they are described in Figure 2. This sensitivity analysis does not change the results fundamentally. The high harvest scenario still gives a smaller carbon stock than the low harvest scenario, also in the long term.

The next question analyzed in the fourth essay is whether there could be climate benefits of increased harvesting, despite the drop in the forest's carbon stock, if bioenergy replaces fossil fuels. Two cases are considered. In the first case, it was assumed that the wood is used as the raw material for manufacturing pellets. The pellets are assumed to replace coal in power plants. This is a relevant example because use of pellets to replace coal in power plants is taking place on an increasing scale in Europe (Lamers, Marchal, Heinimö, & Steierer, 2014). Furthermore, at the time of writing a large plant for production of pellets had recently been established on the west coast of Norway.[16]

The second example considers wood used to produce second-generation liquid biofuels. This example is relevant as NEA (2010) presented ambitious scenarios for the production of second-generation liquid biofuels based on wood. Moreover, recently the Norwegian company Statkraft and the Swedish company Söder are planning to start large scale production of second-generation liquid biofuels based on wood at Tofte in Norway.

Along the lines of Fargione et al. (2008), the fourth essay applies the concept *carbon debt,* which is defined as the net change in the accumulated emissions of carbon, taking into account both the drop in the forest's carbon stock due to the higher harvesting level and emission reductions when bioenergy replaces fossil fuels. Figure 4 illustrates the concept. The double-lined curve represents the drop in the forest's carbon stock that follows from increased harvesting. However, to find the net effect on atmospheric carbon, life cycle studies typically assume that the amount of bioenergy replaces a corresponding amount of fossil fuels, usually on a 1 kWh bioenergy against 1 kWh fossil energy basis. The dashed curve in Figure 4 represents that case, i.e. the net effect on accumulated emissions of CO_2 to the atmosphere when it is assumed that the supply of bioenergy replaces fossil fuels on a 1 kWh against 1 kWh basis. I return to the lack of realism in this approach due to leakage effects.

Nevertheless, with this approach there will be an initial period from t_0 to t_1 with enhanced concentration of CO_2 in the atmosphere, see Figure 4. The length of this period was

[16] BioWood at Averøya outside Kristiansund. The plan was to produce pellets for the European coal power plants based on Norwegian wood and was in an evaluation by Sjølie and Solberg (2009) considered to be environmentally beneficial. The project went bankrupt in 2014 and production was closed down.

by Fargione et al. (2008) labeled *the payback time of the carbon debt*. After time t_1 the CO_2 concentration of the atmosphere will be lower than in the case without bioenergy.

In the fourth essay, the payback time is found to be around 340 years if the harvest is used as raw material in the production of second-generation liquid biofuels. If the harvest instead is processed to pellets and replaces coal in power plants, the pay back time is found to be approximately 190 years.

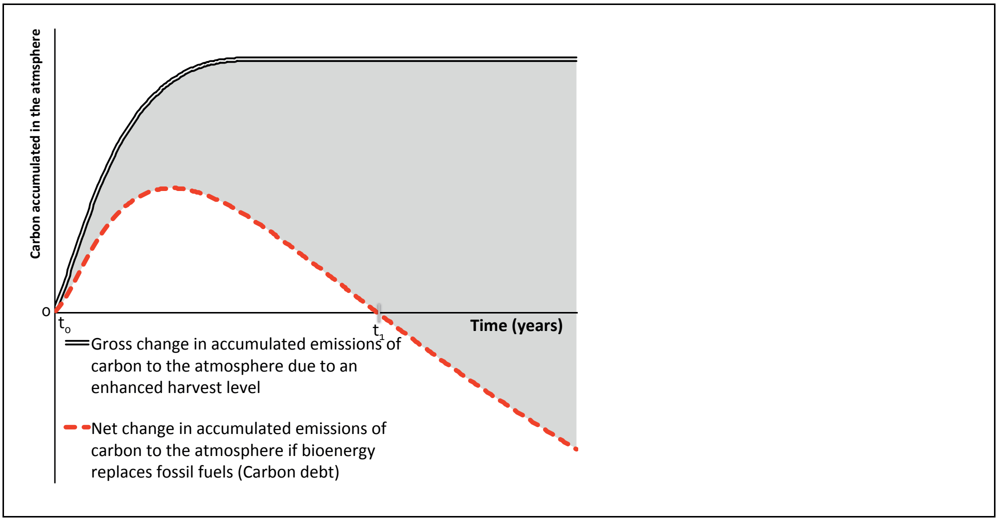

Figure 4. The change in accumulated emissions of carbon to the atmosphere due to a higher harvest level. The double-lined curve shows the case with no replacement of fossil energy, while the dashed line shows the case where bioenergy replaces fossil energy on 1 kWh bioenergy against 1 kWh fossil energy basis. Taking market effects into account means that a result within the grey area becomes more likely, see discussion in the sixth essay.

1.13. The global warming effect of wood fuels – summary of the fifth essay

Because bioenergy traditionally has been considered to be carbon neutral, CO_2 released from combustion of bioenergy (biogenic CO_2-emissions) has implicitly been given a global warming potential (GWP) factor of zero, for example in most LCA-studies.[17] With a GWP-factor of zero it has also been natural to exclude biogenic CO_2-emissions from carbon taxes and emissions trading regimes.

[17] GWP is a metric used to compare the climate impacts of GHGs. GWP quantifies the cumulative potential warming effect of a pulse of GHGs over a specified timeframe. GWP is a relative measure and the GWP of CO_2 is the benchmark and given the ratio 1.

However, as argued in the fourth essay, it is misleading to consider biogenic CO_2 as carbon neutral, at least CO_2 from combustion of wood from boreal forests. Other studies have come to the same conclusion, see for example Haberl et al. (2012), B. Holtsmark (2013a), Schulze et al. (2012), and Searchinger et al. (2009). The question is then how to quantify the warming potential of biogenic CO_2.

As a response to this new consensus and the questions that then arises, Cherubini, Peters, Berntsen, Strømman, and Hertwich (2011) introduced the concept GWP_{bio}, which was proposed as an indicator of the net potential warming of CO_2 released by combustion of biomass. GWP_{bio} should take into account not only the CO_2-pulse from combustion of the biomass, but how the harvest influences the net carbon flux between the considered forest stand and the atmosphere after the harvest, as the trees regrow. Later, also Cherubini, Strømman, and Hertwich (2011), Guest, Cherubini, and Strømman (2013), and Pingoud, Ekholm, and Savolainen (2012) presented estimates of GWP_{bio}. The mentioned studies found GWP_{bio} to be in the interval 0.34–0.62 when slow-growing forest stands were considered. The fact that these estimates are significantly below 1 could lead to the conclusion that bioenergy from slow-growing forests is 'an attractive climate change mitigation option' (Cherubini, Strømman, et al., 2011, p. p. 65).

The fifth essay, which is published in *GCB Bioenergy* (B. Holtsmark, 2015b), questions the results of those studies. The essay finds that the mentioned studies applied too restrictive models, for example abstracting from the dynamics of important carbon pools such as natural deadwood and soil carbon. Moreover, only Pingoud et al. (2012) included a representative baseline scenario. The other studies made the assumption that, if not harvested, there is no further growth and accumulation of carbon in a mature stand.

The fifth essay presents a different method for quantifying GWP_{bio}, by including a more comprehensive model of the dynamics of the carbon fluxes between the considered forest stand and the atmosphere. Moreover, the proposed method compares the harvest scenario with a no-harvest baseline scenario that takes into account that stands are usually harvested before growth has culminated (Faustmann 1849). Hence, there is growth and thus carbon capture also in the no-harvest scenario, although at a declining rate. Finally, the proposed method includes modeling the dynamics of all the forest's main carbon pools, including soil carbon, the pool of natural deadwood, and harvest residues, in addition to the stems. Including all carbon pools in the model is important because harvesting influences the dynamics of these pools, and thus the net carbon flux.

An important methodological difference between the fourth and the fifth essay should be mentioned. The fourth essay assumed as a simplification that CO_2-emissions accumulate in the atmosphere with no decay function, i.e. that CO_2 emitted to the atmosphere stays in the atmosphere forever. In agreement with other studies related to GWP_{bio}, the fifth essay makes this more sophisticated through application of the Bern 2.5CC carbon cycle model and its decay function based on Joos and Bruno (1996), Joos et al. (1996), and Joos et al. (2001). This model takes into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere and the sea. The Bern 2.5CC model is also applied to all the fluxes of CO_2 between the considered stand and the atmosphere, for example the flux of CO_2 due to decomposition of natural deadwood and harvest residues left on the forest floor.

With the methodological improvements described above, the resulting GWP_{bio}-estimates are found to be 1.5 when no residues are harvested together with the stems. If 25 per cent of the residues are harvested, a share that corresponds to most of the tops and branches, GWP_{bio} is found to be 1.25. In other words, the estimates of GWP_{bio} was found to be two to three times as high as the estimates of GWP_{bio} found in other studies, and also significantly above GWP of fossil CO_2 when a 100 years time horizon was applied. Hence, the climate impact of bioenergy from slow growing forests seems to be higher than the climate impact of fossil fuels combustion, when a 100 years time horizon is applied.

A short comment is suitable on the result that GWP_{bio} is found to be lower when residues are harvested together with the stems. This might appear paradoxical as combustion of residues in addition to the stems increases the initial pulse of CO_2. However, keep in mind that GWP_{bio} is a relative measure (the warming potential per unit CO_2 of the initial pulse). If the residues had been left on the ground for decomposition, it would also gradually caused CO_2 emissions, increasing the warming potential per unit CO_2 in the initial pulse from combustion of the stems.

It also might appear paradoxical that the climate impact of CO_2 from bioenergy is found to be larger than the climate impact of CO_2 from fossil fuels. There are simple explanations to this result. First, the release of CO_2 from the decomposition of the residues left on the forest floor is significant and it comes in addition to the pulse-emission generated by the combustion of the harvested stems. Second, the dynamics of the pool of carbon stored in natural deadwood are important, and especially the lower accumulation of natural deadwood in the harvest scenario compared to the baseline no-harvest scenario. Third, in the no-harvest scenario, there is continued forest growth although at a declining rate, and there is continued accumulation of dead organic matter. Finally, the release of carbon from the soil after harvesting plays a role, although not a major one.

Nonetheless, when a very long time horizon, for example 500 years, is found more relevant, the fifth essay, as other studies, find that bioenergy becomes attractive from a climate perspective.

As mentioned above, previous studies estimated the GWP_{bio} to be significantly lower than found in the fifth essay. As the models applied in those studies are less comprehensive, an illustrative test would be to simplify the model applied in the fifth essay such that the applied model becomes similar to the models applied in earlier studies of GWP_{bio} and check whether the estimates of GWP_{bio} then are in agreement as well. Such tests were carried out and the fifth essay reports results of those model simulations. The results reported are in good agreement with results reported in the mentioned studies. This strengthens the conclusion that calculating the climate impacts of bioenergy from forests should be based on models that take into account the dynamics of all the forests' carbon pools and that previous estimates of the climate effects of bioenergy are too low.

1.14. A comparison of the global warming effects of wood fuels and fossil fuels – summary of the sixth essay

Like the fifth essay, the sixth essay applies the concept GWP_{bio} to quantify the global warming effect of bioenergy. The sixth essay is a slightly revised version of a paper published in *GCB Bioenergy* (B. Holtsmark, 2015a).[18] The sixth essay applies basically the same model of a forest stand as the fifth essay although a slightly different model for decomposition of forest residues was applied in the sixth essay. However, the sixth essay extends the analysis along three lines. First, it includes the cooling effects of increased albedo after clear-cutting. Second, it includes a comparison of the warming impact of bioenergy and fossil fuels, taking the CO_2-emissions per unit of energy into account. Third, the sixth essay follows up the discussion of the length of the payback time of the carbon debt introduced in the fourth essay.

With regard to the albedo effect, the essay adopts the methods and parameters applied by Cherubini, Bright, and Strømman (2012). They assumed that clear-cutting of a considered stand results in an immediate rise in albedo, not least because there will be a continuous snow surface during the winter season with high reflection of sunlight, if the stand has been clear-

[18] In addition to the main case with a climate sensitivity of 3 ºC, B. Holtsmark (2015a) considered a case with a climate sensitivity of 4.5 ºC. However, the way the parameters of the Bern 2.5CC were changed in this case could be criticized. The case is therefore left out in the sixth essay. Moreover, there are made some minor editing of the text.

cut recently. The albedo effect is then gradually reduced as regrowth takes place and the surface becomes less reflective during the winter season.[19]

When the albedo effect is not taken into account, the estimates of GWP_{bio} are almost identical to the results found in the fifth essay. The small differences are due to the slightly different model for decomposition of dead organic matter. When albedo effects are included in the calculations, the GWP_{bio} estimates become significantly lower. When residues (tops and branches) are collected together with the stems, the GWP_{bio} estimate drops to 0.75, when a time horizon of 100 years is applied. In the case without the collection of any residues, GWP_{bio} was found to be 1.1.

Next, the sixth essay carries out a comparison of the warming impact of wood fuels and fossil fuels. The result is that, when there are no albedo effects of harvesting and either a 100-year or a 20-year time horizon is applied, the warming impact of wood fuels is significantly higher than the warming impact of fossil fuels. The results are more ambiguous when an albedo effect of harvesting is included. The performance of wood fuels compared to fossil fuels then depends on whether residues are collected together with the stems. If residues are collected, the warming effect of wood fuels per unit of energy produced is approximately at the same level as oil when a 100-year time horizon is applied. If residues are not harvested, the warming effect of wood fuels is approximately at the level of coal when a 100-year time horizon is applied. If a time horizon of 500 years is applied, wood fuels have a smaller warming effect than all three types of fossil fuels, irrespective of the assumptions made.

Finally, the sixth essay leaves the single harvest approach and considers a permanent increase in the harvesting level, as also was done in the fourth essay. Moreover, comparisons are made with the warming effect of oil, coal, and natural gas. A methodological improvement compared to the fourth essay is to apply the Bern 2.5CC carbon cycle model. Both the limiting cases with no substitution and full substitution (1 kWh bioenergy replaces 1 kWh fossil fuels) were considered in order to capture the full range of possible outcomes.

As the fourth essay, the sixth essay provides estimates of the payback time of the carbon debt. This payback time was found to be 140 years if there is full substitution of coal (1 kWh bioenergy replaces 1 kWh coal). If bioenergy replaces oil or gas, the payback time is significantly longer.

If less optimistic assumptions are made about how much fossil fuels are replaced by the increased supply of bioenergy, the payback time becomes longer. The inclusion of the

[19] Lutz and Howarth (2014) study the importance of albedo for forest management in case of temperate forests south of the boreal forest belt.

albedo effects of harvesting results in a picture that is significantly more in favor of bioenergy, with shorter payback times. If there is full substitution of coal, the albedo case means that there is a net cooling effect of harvesting from day one. However, if less substitution is assumed, the picture will be less in favor of bioenergy.

The payback time found in the sixth essays is somewhat shorter than found in the fourth essay. One reason for this is that the sixth essay applies the Bern 2.5CC carbon cycle model, while the fourth essay applied a simple accumulation model with no decay function.

1.15. Forest management when there is a social cost of CO_2-emissions – summary of the seventh essay

As the preceding three essays, the seventh and last essay studies forest management in relation to the climate issue. However, the approach taken is different. The three preceding essays studied how harvesting a slow growing boreal forest influences global warming when the harvest is used as bioenergy. The fourth and the sixth essays in addition compared the warming effect of bioenergy with the warming effect of fossil fuels. The seventh essay has a more classical economic approach and has as starting point that there is a social cost of carbon emissions and analyses how this should influence forest management. The seventh essay is a joint work with Michael Hoel and Katinka Holtsmark. It is published in *Journal of Forest Economics* (Hoel, Holtsmark, & Holtsmark, 2014).

The approach taken in this essay is relevant in a situation where there is a tax or a similar instrument related to combustion of fossil fuels that corresponds to the social cost of carbon. The basic research question studied is how forests should be managed in this situation, given that a certain share of the harvest is used for bioenergy, while the remaining share is used as building material or other durable goods. To simplify the analysis, it is assumed that the social cost of carbon is assumed to be constant over time, which means that the present value is decreasing over time.

Faustmann (1849) was the first to develop a correct formula (the Faustmann Rule) for determination of the length of the rotation period when a forest owner's goal is to maximize the discounted yield, taking account of the discounted yield from all future rotations. The main contribution of the essay is to develop an adjusted Faustmann Rule when there is a social cost of carbon emissions, taking into account the dynamics and interactions of the forest's multiple carbon pools. Numerical examples illustrate the theoretical results.

Among other theoretical studies of the issue, van Kooten, Binkley, and Delcourt (1995) and McDermott et al. (2015) represent to my knowledge the most thorough studies.

They applied a multi-rotation infinite time horizon model and provided an adjusted Faustmann Rule when there is a social cost of carbon emissions. However, the theoretical framework of these two studies did not incorporate the dynamics of important carbon pools such as roots, stumps, tops and branches, harvest residues and naturally dead organic matter, which the seventh essay shows are important elements in construction of an adjusted Faustmann Rule.

Asante and Armstrong (2012) is another theoretical contribution, see also Asante, Armstrong, and Adamowicz (2011). In contrast to van Kooten et al. (1995) and McDermott et al. (2015), they included the forests' multiple carbon pools in their model. At the same time they considered a single rotation model only and their time horizon was limited to the length of the single rotation. B. Holtsmark, Hoel, and Holtsmark (2013) discussed the results of Asante and Armstrong (2012) and found that their main results followed from their limited time horizon and could be misleading. This made evident the need for a theoretical, multi-period infinite horizon analysis of the issue, which includes the dynamics of the forests' main carbon pools. Therefore, the seventh essay presents a comprehensive theoretical analysis that combines the multi-rotation infinite time horizon model of van Kooten et al. (1995) with the multiple carbon pools approach of Asante and Armstrong (2012) and Holtsmark et al. (2013).

The findings of the seventh essay could be summarized as follows. First, consider a forest with positive net commercial profit from harvesting. In that case, if the rotation period that maximizes social welfare is finite, the adjusted rule implies that the optimal rotation length is strictly increasing in the social cost of carbon. Depending on the parameters, it may be the case that a finite rotation length is optimal no matter how large is the social cost of carbon emissions. There may also exist a threshold value for the social cost of carbon, above which the stand should not be harvested. It could here be mentioned that the simulations with the numerical forest model show that for reasonable discount rates and parameter values, a threshold value actually exists above which the forest should not be harvested.

Second, consider the case when there is *negative commercial profit* from harvesting. If there is a positive social cost of carbon emissions that is lower than a certain threshold level, then it is optimal to never harvest the stand. If the social cost of carbon is *above* the mentioned threshold level, depending on the parameters, it could in theory give a social surplus to harvest. If so, then the adjusted Faustmann Rule implies that the optimal rotation length is strictly *decreasing* in the social cost of carbon. It is difficult to give good intuition to this result. However, a social surplus from harvesting when the commercial profit is negative appears to be an unlikely case. Numerical simulations showed that for reasonable discount rates and parameter values, the stand should never be harvested if there is a negative commercial profit.

The main driver of the results of the seventh essay is the assumption that the present value of the social cost of carbon is decreasing over time – emissions in the future are preferred over emissions today. This seems a reasonable assumption, and is elsewhere in the literature often either assumed or derived from other assumptions of the analysis. A single harvest leads to an increase in the stock of carbon in the atmosphere in the short run, and the damage resulting from this increase would have been postponed with a longer rotation period.

Compared to other theoretical studies, the contribution of the seventh essay is to investigate the issue in a considerably less restrictive theoretical framework. We take into account that less than half of the carbon in the forests' biomass is contained in the tree trunks. Tops, branches, roots and stumps constitute approximately half of the carbon stored in living biomass, and to the extent that these components are not harvested together with the trunks, they will gradually decompose and release carbon to the atmosphere. The dynamics of these carbon pools as well as the stock of natural deadwood is included in both the theoretical and numerical analyses. In addition, we allow an exogenous fraction of tops, branches, roots and stumps to be harvested and used for energy purposes. And finally, the dynamics of a stock of carbon stored in building materials and furniture is also taken into account. With our less restrictive approach, including both multiple rotation periods and multiple carbon pools in the analysis, the threshold value of the social cost of carbon above the threshold value at which harvest should not take place, is significantly lower than found in studies with a more restrictive approach. The multiple-carbon-pool-approach also means that the effect of a social cost of carbon on the length of the rotation period is significantly stronger than found in previous theoretical studies with more restrictive models. To fully understand the mechanisms behind the effect of a social cost of carbon on the optimal length of the rotation period, our less restrictive model turns out to be important. We found that increasing the share of residues harvested and/or the share of stems used for durable storage in buildings and furniture reduces the effect of a social cost of carbon on the optimal rotation period. Conclusions regarding the effect on the optimal rotation periods of changes in harvesting procedures or use of harvested material might potentially have important policy implications.

1.16. Closing comments

Finally, a few words about what can be concluded from this thesis, and some unresolved issues that have become more visible.

Regarding the first three essays, they do not give any final answers on how to make international cooperation on climate change more effectively. Hopefully, however, they give some contributions to the accumulation of knowledge related to important questions. The games presented in the second and third essays lead to conclusions that question the benefits of emissions trading. However, the exercises of these two essays are based on stylized models and are not sufficiently complete to warrant any strong policy implications. It is also important to note that other contributions provide conclusions that point in a different and more optimistic direction. Nevertheless, the findings of the second and third essays demonstrate that there are some mechanisms that are important to understand and be aware of in the design of agreements with emissions trading. The fact that the literature on the field gives divergent conclusions also emphasizes the need for more research in the field. As emissions trading is central to international cooperation on climate change, this could be important.

Regarding the last four essays about bioenergy from slow-growing boreal forest, they provide the basis for somewhat stronger conclusions. What seems pretty clear is that the classical assumption that bioenergy is carbon-neutral does not hold. The last four essays clearly show that increased logging for energy purposes in boreal forests could increase the concentration of CO_2 in the atmosphere for a long time, probably throughout the 21st century and even further into the future. At the same time, there is little doubt that on the very long term, such a policy could lead to lower CO_2 content in the atmosphere, if bioenergy replaces fossil fuels efficiently. Without efficient replacement of fossil fuels, increased use of bioenergy could amplify the CO_2 problem.

However, also when it comes to the last four essays of the thesis, the results should not be overinterpreted. Although I find that earlier studies might have overestimated climate benefits of bioenergy from forests, this does not mean that bioenergy in general is harmful. Much of today's bioenergy is made of waste from different wood-based industries. If such waste is used for energy purposes and replaces fossil fuels, it gives climate benefits. The primary purpose of the thesis is not to study that type of bioenergy, but rather to study whether increased logging for energy purposes gives climate gains. This is a relevant issue since harvesting is increasing in several countries just to increase the supply of bioenergy (Lamers et al., 2014). In this perspective, the mentioned findings are relevant.

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Essay 1

Renegotiation-Proof Climate Agreements with Full Participation: Conditions for Pareto-Efficiency

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Renegotiation-Proof Climate Agreements with Full Participation: Conditions for Pareto-Efficiency

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Abstract Recent contributions show that climate agreements with broad participation can be implemented as weakly renegotiation-proof equilibria in simple models of greenhouse gas abatement where each country has a binary choice between cooperating (i.e., abate emissions) or defecting (no abatement). Here we show that this result carries over to a model where countries have a continuum of emission choices. Indeed, a Pareto-efficient climate agreement can always be implemented as a weakly renegotiation-proof equilibrium, for a sufficiently high discount factor. This means that one need not trade-off a "narrow but deep" treaty with a "broad but shallow" treaty.

Keywords International environmental agreements · Non-cooperative game theory · Pareto efficiency · Weak renegotiation proofness

1 Introduction

In simple dynamic models of international environmental public good provision, such as mitigation of climate change, Barrett (1999, 2002) has argued that there is a trade-off between "narrow but deep" and "broad but shallow" treaties: either only a few countries participate each with a large abatement, or many countries participate each with a small abatement.

By applying the Barrett (1999) model, where each country has a binary choice between *cooperating* (i.e., abate emissions) or *defecting* (no abatement), Asheim et al. (2006) show that extended participation is feasible. They show that participation can essentially be doubled in a two-region world.

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The analysis of Asheim et al. (2006) exploits the fact that Barrett (1999) considers only strategy profiles with a special structure, namely where there is a subset of participating countries ("signatories") in a treaty, and where a defecting signatory is punished by having *all* other signatories defect in the next period (only). Then, if there are too many signatories, these will gain by renegotiating back to cooperation without imposing the punishment, thereby undermining the credibility of the equilibrium. Asheim et al. (2006) limit the number of punishing countries by letting a defection be punished only by the other signatories in the same region, while the signatories in the other region continue to cooperate.

The possibility that only a subset of the signatories within a global treaty punishes a deviant is investigated to its logical conclusion by Froyn and Hovi (2008) within the binary choice model of Barrett (1999). They show that full participation can indeed by implemented as a weakly renegotiation-proof equilibrium.

It is still an open question whether these insights carry over to a continuum choice model like the one considered by Barrett (2002). To reach a Pareto-efficient agreement in such a setting, one need not only agree on a *broad* treaty with full participation, but also a *deep* treaty where each country's abatement is at an efficient level.

By considering a model where the public benefits of emission abatement are linear and private costs of emission abatement are quadratic, we show as our main result (Proposition 1) that such an efficient broad and deep treaty can always be implemented as a weakly renegotiation-proof equilibrium, provided that the discount rate is sufficiently low and the number of countries is sufficiently small. In the same context we also show as an additional result (Proposition 2) how depth, but not broadness, must be compromised for high discount rates and a large number of countries.

Since low time discounting and a short detection lag contribute to a low discount rate, and high time discounting and a long detection lag contribute to a high discount rate,[1] these results mean that

- low time discounting and a short detection lag combined with a small number of countries contribute to the feasibility of a Pareto-efficient agreement, with full participation and efficient depth,
- high time discounting and a long detection lag combined with a large number of countries undermine the feasibility of Pareto-efficient depth of cooperation. However, such a shallower agreement still allows full participation.

Both results follow from a technical result (Theorem 1), in which we characterize the set of weakly renegotiation-proof equilibria for a class of repeated game strategy profiles, where punishments last for one period only (Abreu 1986; van Damme 1989), but where participation in the treaty, participation in the punishment, the depth of the treaty and the severity of the punishment are parameters which are allowed to vary.

Linear benefits of abatement represent a simplification. Asheim et al. (2006) show that their result holds also when abatement yields non-linear benefits. It would be of value to check whether our findings carry over to a less restrictive model with non-linear benefits of abatement and asymmetric countries, as considered in the two-country model in Finus and Rundshagen (1998). However, we remain within the context of linear benefits in the present paper, as it is an analytically tractable setting which allows us to characterize weak renegotation-proofness.

Sections 2 and 3 present our results, while Sect. 4 contains a discussion of their relevance. All proofs are relegated to an appendix.

[1] If r is the positive rate of time discounting, and Δ is the detection lag (= period length), then the per-period discount factor, δ, is given by $\delta = \int_0^{\Delta} e^{-rt} dt$ and the per-period discount rate is $1 - \delta$.

2 Main Result

Consider a world with $n \geq 2$ countries, where $N = \{1, \ldots, n\}$ denotes the set of all countries. The countries interact in periods (or "stages") $0, 1, 2, \ldots$. The countries are identical in all relevant characteristics. In every period, each country i must choose a non-negative level of abatement q_i of greenhouse gas emissions. Each country i's periodic payoff, relative to the situation where no country abates, is given by

$$\pi_i = b \sum_{j=1}^{n} q_j - \frac{c}{2}(q_i)^2 , \tag{1}$$

where b is the marginal benefit from abatement (which is a pure public good that benefits each and every country), and $(c/2)(q_i)^2$ represents the total abatement costs of country i. We assume that $b, c > 0$.

Following Barrett (1999, 2002) and Asheim et al. (2006), we abstract from the future benefits of abatement (which of course are important in the climate change setting; cf. Dutta and Radner 2007), meaning that the situation can be modeled as an infinitely repeated game, with a stage game where the countries simultaneously and independently choose abatement levels, and receive payoffs according to (1).

The stage game has a unique Nash equilibrium where each country abates

$$q^1 = \frac{b}{c} .$$

Actually, for each country, q^1 strictly dominates any other action of the stage game and is thus its unique best response independently of what the other countries' abatement levels are. However, the unique symmetric Pareto-efficient abatement profile entails that each country abates

$$q^n = \frac{nb}{c} . \tag{2}$$

Hence, the Pareto-efficient abatement is n times the abatement level in the Nash equilibrium of the stage game, cf. Barrett (2002, p. 540). In particular, the n countries would want to agree on implementing

$$\mathbf{a} = \underbrace{(q^n, \ldots, q^n)}_{j \in N}, \underbrace{(q^n, \ldots, q^n)}_{j \in N}, \ldots ,$$

where each country contributes to the Pareto-efficient total abatement in a cost-efficient manner in every period.

In the absence of third-party enforcement, such a Pareto-efficient agreement needs to be self-enforcing, where deviations from this agreement—leading to a short-run benefit for the deviating country—is deterred through the threat of future punishment, which must also be self-enforcing. Here, "self-enforcing" refers to the play of a non-cooperative equilibrium of the infinitely repeated game; the analysis of such equilibria requires the introduction of some game-theoretic formalism.

A history at the beginning of stage t describes the countries' abatement levels in periods $0, \ldots, t-1$:

$$(q_1(0), \ldots, q_n(0)), (q_1(1), \ldots, q_n(1)), \ldots, (q_1(t-1), \ldots, q_n(t-1)) .$$

A strategy σ_i for country i is a function which for every history, including the "empty" history at the beginning of stage 0, determines an abatement level for player i. Country i's average discounted payoff in the repeated game is given by

$$\left(1-\delta\right)\sum_{t=0}^{\infty}\delta^t\pi_i(t)\,, \tag{3}$$

where $\delta \in (0, 1)$ is the discount *factor*, and $\pi_i(t)$ is country i's periodic payoff according to (1) in stage t when the abatement profile is $(q_1(t), \ldots, q_n(t))$. A strategy profile $(\sigma_1, \ldots, \sigma_n)$ is a subgame-perfect equilibrium if, for every history, there is no country that can increase its discounted payoff by deviating from its strategy, provided that all other players follow their strategies in the continuation of the game. A subgame-perfect equilibrium is weakly renegotiation-proof (Farrell and Maskin 1989) if there do not exist two histories such that all players strictly prefer the continuation equilibrium in the one to the continuation equilibrium in the other.

We can now state our main result.

Proposition 1 *For any positive integer $n \geq 2$ and positive real numbers b and c, there exists a weakly renegotiation-proof equilibrium with* **a** *as the equilibrium path if the countries' repeated game payoffs are discounted by discount factor δ in the interval $\left[(n-1)/n,\ 1\right)$.*

In the remainder of this section, we describe a strategy profile with an uncomplicated structure, leading to the Pareto-efficient agreement **a**. According to a general theorem stated in the next section, this strategy profile is a weakly renegotiation-proof equilibria for $\delta \geq (n-1)/n$, thereby proving Proposition 1. Since $\delta \geq (n-1)/n$ is equivalent to the discount *rate*, $1-\delta$, not exceeding $1/n$, this shows that **a** can be implemented in a self-enforcing manner, provided that the discount rate is sufficiently low and the number of countries is sufficiently small. In the next section we also consider slightly more complicated renegotiation-proof equilibria that implement **a** in a self-enforcing manner even if $\delta < (n-1)/n$, provided that (10) and (11) are satisfied.

Following Abreu (1988) we consider simple strategy profiles, consisting of an equilibrium path to be implemented, and n punishment paths, one for each player. The equilibrium path is followed until a single country deviates, an occurrence that leads to this player's punishment path being initiated in the next period. Also any unilateral deviation from a punishment path leads to the initiation of the (new) deviating country's punishment path. Through these rules, the $n+1$ paths specify a strategy for each player. Hence, with **a** as the equilibrium path, we need only construct the n punishment paths and show that the resulting simple strategy profile is indeed a weakly renegotiation-proof equilibrium.

To construct the path, $\mathbf{p}_i$, used to punish country i, consider a function which for any n determines a subset $P_i(n) \subset N$ of punishing countries. Let $P_i(n)$ have the properties that (1) $i \notin P_i(n)$ and (2) the number of countries in $P_i(n)$ equals $n/2$ if n is even and $(n+1)/2$ if n is odd. The interpretation is that each country in $P_i(n)$ punishes a unilateral deviation by country i by choosing the abatement level q^1 in the period immediately following country i's deviation, while countries in $N\backslash P_i(n)$ (including country i) abates at the Pareto-efficient level q^n. In the subsequent periods all countries return to the Pareto-effcient abatement level. Hence, the punishment path of country i is:

$$\mathbf{p}_i = (\underbrace{q^1, \ldots, q^1}_{j\in P_i(n)}, \underbrace{q^n, \ldots, q^n}_{j\in N\backslash P_i(n)}), (\underbrace{q^n, \ldots, q^n}_{j\in N}), (\underbrace{q^n, \ldots, q^n}_{j\in N}), \ldots .$$

In the next section we show that, for any positive integer $n \geq 2$ and positive real numbers b and c, the simple strategy profile described by the $n+1$ paths $(\mathbf{a}, \mathbf{p}_1, \ldots, \mathbf{p}_n)$ is a weakly renegotiation-proof equilibrium if the discount factor, δ, satisfies $\delta \geq (n-1)/n$. Having $n/2$ (or $(n+1)/2$ if n is odd) countries punishing for one period by choosing their best response q^1 of the stage game is sufficiently many to discipline a potential deviator, while being sufficiently few to ensure that each punisher in $P_i(n)$ gains at least as much by reducing its abatement as it loses by the fact that the other countries in $P_i(n)$ abate less.

3 Participation and Punishment

In this section we consider a class of strategy profiles in the repeated games described in Sect. 2, and establish as Theorem 1 under what parameter values members of this class are weakly renegotiation-proof equilibria. Since the strategy profiles used to establish existence in Proposition 1 are members of this class, this result follows as a corollary to Theorem 1. We also present Proposition 2, our result on the maximal treaty depth for low discount factors and a large number of countries.

Fix the set of countries $N = \{1, \ldots, n\}$. Let $M = \{i_i, \ldots, i_m\}$ $(\subseteq N)$ be the signatories to a treaty, with m members (where $0 < m \leq n$). The treaty specifies that the agreement $\mathbf{a}^s$ be implemented, where

$$\mathbf{a}^s = (\underbrace{q^s, \ldots, q^s}_{j \in M}, \underbrace{q^1, \ldots, q^1}_{j \in N \setminus M}), (\underbrace{q^s, \ldots, q^s}_{j \in M}, \underbrace{q^1, \ldots, q^1}_{j \in N \setminus M}), \ldots ,$$

and $q^s = sb/c$ with $s > 1$. Hence, the signatories of the treaty abate s times the level that constitutes the individual country's best response, while the non-signatories choose the best response level.

Since each signatory is not playing a best response of the stage game, a deviation from the agreement by a signatory must be prevented by the threat of future punishment. To construct the path, $\mathbf{p}_i^s$, used to punish country $i \in M$, consider a set $P_i \subset M$ of punishing countries, satisfying $i \notin P_i$. We assume that $|P_i|$, the number of countries in P_i, is the same for all $i \in M$, while of course the identities of the countries may not (and can not) be the same. Write $k = |P_i|$. Each country in P_i punishes a unilateral deviation by country i by choosing the abatement level $q^p = pb/c$ in the period immediately following country i's deviation, where $p \geq 0$. The other signatories including country i (i.e., the countries in $M \setminus P_i$) abate at the agreed upon level q^s. In the subsequent periods all signatories return to the agreed upon level q^s. All non-signatories (i.e, $j \in N \setminus M$) continue to play their best response q^1 throughout. Hence, the punishment path of country $i \in M$ is:

$$\mathbf{p}_i^s = (\underbrace{q^p, \ldots, q^p}_{j \in P_i}, \underbrace{q^s, \ldots, q^s}_{j \in M \setminus P_i}, \underbrace{q^1, \ldots, q^1}_{j \in N \setminus M}),$$
$$(\underbrace{q^s, \ldots, q^s}_{j \in M}, \underbrace{q^1, \ldots, q^1}_{j \in N \setminus M}), (\underbrace{q^s, \ldots, q^s}_{j \in M}, \underbrace{q^1, \ldots, q^1}_{j \in N \setminus M}), \ldots .$$

Since each non-signatory is playing a best response of the stage game, a deviation from the agreement by a non-signatory requires no punishment. Hence, even if a non-signatory unilaterally deviates from $\mathbf{a}^s$ or $\mathbf{p}_i^s$ for some $i \in M$, the path in question is simply continued, meaning that any such unilateral deviation is followed by $\mathbf{a}^s$. Hence, formally, the punishment path of country $i \in N \setminus M$ equals $\mathbf{a}^s$.

The simple strategy profile determined by the $n + 1$ paths

$$(\mathbf{a}^s, \mathbf{p}^s_{i_1}, \ldots, \mathbf{p}^s_{i_m}, \underbrace{\mathbf{a}^s, \ldots, \mathbf{a}^s}_{j \in N \setminus M}) \tag{4}$$

corresponds to what Froyn and Hovi (2008) refer to as "Penance k" . In Theorem 1 we establish under what conditions this strategy profile is a weakly renegotiation-proof equilibrium.

Since the identities of the signatories and the punishing countries do not matter, as all countries are identical, the conditions of Theorem 1 depend on only the parameters δ (the discount factor), n (the total number of countries), m (the broadness of the treaty; i.e., the number of signatories), k (the number of punishing countries), s (the depth of the treaty), and p (the severity of the punishment). In fact, δ, k, s and p are sufficient to decide whether the simple strategy profile determined by the paths in (4) is weakly renegotiation-proof, while n and m do not matter as long as they satisfy $n \geq m > k$.

Theorem 1 *The simple strategy profile determined by (4) with $s > 1$ and $p \geq 0$ is a weakly renegotiation-proof equilibrium for $\delta \in (0, 1)$ if and only if k, s and p satisfy $s > p$ and*

$$\frac{1}{2\delta} \cdot \frac{(\max\{s-1, |p-1|\})^2}{s-p} \leq k \leq \frac{1}{2}(s+p)\,. \tag{5}$$

In the kind of weakly renegotiation-proof equilibria used to establish existence in Proposition 1, we have that

$$s = n \quad \text{and} \quad p = 1\,.$$

Then expression (5) simplifies to

$$\frac{1}{\delta}(n-1) \leq 2k \leq n+1\,. \tag{6}$$

If n is even and $k = n/2$, then the right inequality is satisfied, and the left inequality is satisfied if

$$\delta \geq \frac{n-1}{n}\,. \tag{7}$$

If n is odd and $k = (n+1)/2$, then the right inequality is satisfied, and the left inequality is satisfied if

$$\delta \geq \frac{n-1}{n+1}\,,$$

which is implied by (7). In either cases, $\delta \in \big[(n-1)/n,\ 1\big)$ is sufficient, thus showing that Proposition 1 follows as a corollary to Theorem 1.

Proposition 1 shows that a weakly renegotiation-proof Pareto-efficient agreement can be implemented if $\delta \geq (n-1)/n$. Hence, few countries and a high δ, reflecting low time discounting and a short detection lag, contribute to the feasibility of a Pareto-efficient treaty. However, it is of interest to investigate what can be achieved with many countries and a low δ, reflecting high time discounting and a long detection lag. Therefore, in Proposition 2 we analyze the complement case where $\delta < (n-1)/n$.

Proposition 2 *Assume $\delta \in \big(0, (n-1)/n\big)$,*[2] *and consider the simple strategy profile determined by (4) with $s > 1$ and $p \geq 0$. Maximal treaty depth in a weakly renegotiation-proof*

[2] The upper bound $(n-1)/n$ on the discount factor δ ensures that the number of punishing countries k determined by the proposition is smaller than n.

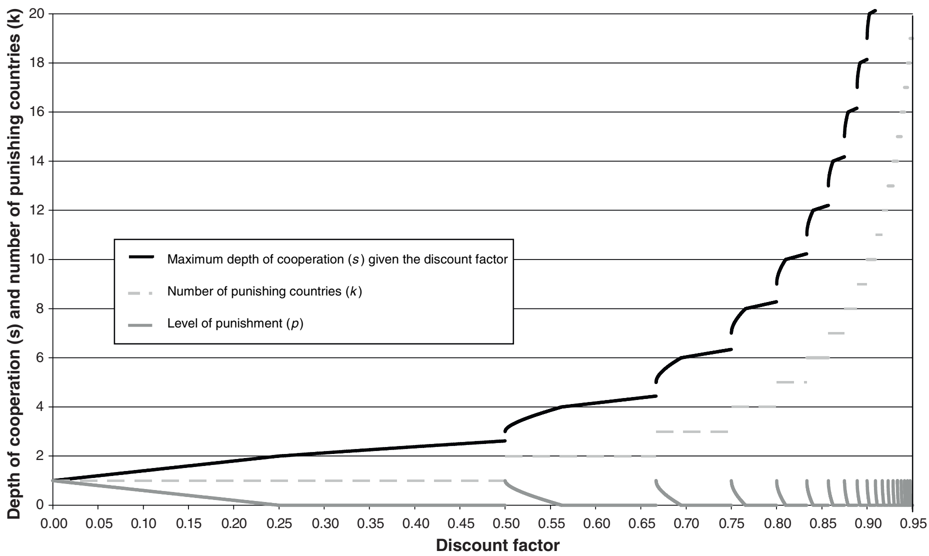

Fig. 1 Maximal treaty depth as a function of the discount factor. The black curve depicts maximal depth of cooperation as a function of the discount factor. The dotted grey, horizontal lines depict the number of punishing countries, while the thin grey curves depict the severity of punishment

equilibrium is given by

$$s(\delta) = 1 + 2k\delta + 2\sqrt{k\delta(1 - k(1 - \delta))}\,, \tag{8}$$

with the severity of punishment given by $p(\delta) = 2k - s(\delta)(\in (0, 1])$*, if there exists* $k \in \mathbb{N}$ *s.t.* $(k-1)/k \le \delta < \left((2k-1)/2k\right)^2$*, and by*

$$s(\delta) = 1 + k\delta + \sqrt{k\delta(2 + k\delta)}\,, \tag{9}$$

with the severity of punishment given by $p(\delta) = 0$*, if there exists* $k \in \mathbb{N}$ *s.t.* $\left((2k-1)/2k\right)^2 \le \delta < k/(k+1)$*. In both cases, the number of punishing countries equals* k $(\in \{1, \ldots, n-1\})$*, and the number of participating countries can be any* m *satisfying* $k < m \le n$*.*

Proposition 2, which is illustrated by Fig. 1, means that Pareto-efficient treaty depth, $s = n$, is feasible if and only if maximal treaty depth, $s(\delta)$, satisfies $s(\delta) \ge n$. This holds under the following conditions:

$$n \text{ odd} \quad \text{and} \quad \delta \ge \tfrac{n-1}{n+1}\,, \tag{10}$$

$$n \text{ even} \quad \text{and} \quad \delta \ge \left(\tfrac{n-1}{n}\right)^2. \tag{11}$$

In case (10), $k = (n+1)/2$ and $p = 1$, and Pareto-efficiency for the lowest discount factor is implemented by the weakly renogotiation-proof equilibrium considered in Proposition 1. In case (11), however, $k = n/2$ is combined with $p = 0$, implying that Pareto-efficiency for the lowest discount factor is implemented by a weakly renogotiation-proof equilibrium with a harsher punishment than the one considered in Proposition 1.

If neither condition (10) nor condition (11) is satisfied, due to a high n and a low δ, then Proposition 2 shows that there is no trade-off between treaty depth and treaty broadness: treaty depth has to give, while full participation is feasible even in a many country world with high time discounting and long detection lags.

In the appendix we prove Theorem 1 and show how Proposition 2 follows from the theorem.

4 Discussion

In this section we first explore the equilibrium concept that underlies the analysis, before discussing our results in the context of climate change.

4.1 Weakly Renegotiation-Proof Equilibrium

In this paper we have applied the game-theoretic concept of "weakly renegotiation-proof equilibrium" (Farrell and Maskin 1989) to study self-enforcing climate agreements. In this section we first discuss what this equilibrium concept means for the significance of our results, before providing numerical illustrations. We also indicate how our findings may have relevance for the ongoing negotiations on a follow-up agreement to the Kyoto Protocol.

A weakly renegotiation-proof equilibrium is a subgame-perfect equilibrium. This presumes that the countries are coordinated in the sense that they all play according to a particular strategy profile described by (4). In other words, the analysis assumes that all countries have agreed upon who will participate in the treaty and how unilateral deviations will be punished. Hence, the framework is designed to analyze how non-compliance can be avoided: it shows how signatories can be induced to fulfill their treaty obligations under the threat of future punishment.

The framework is not suitable for analyzing how coordination is achieved: it is incapable of answering how countries manage to agree on a particular treaty, involving strategies specifying behavior under both compliance and non-compliance. Even though it is of interest to consider a situation where coordination has not yet occurred and where countries seeking a Pareto-efficient climate agreement attempt to punish a would-be-free-rider into joining the effort, this is not an equilibrium of a repeated game, and thus, outside the scope of the present paper.

Weak renegotiation-proofness considers the possibility of a coordinated deviation by *all* countries, but abstracts from the possibility that also a coordinated deviation by a subset of countries can be profitable. Coordinated deviations by a subset of players in a game have been considered by Bernheim et al. (1987) through their concepts "coalition-proof Nash equilibrium" in static games and "perfectly coalition-proof Nash equilibrium" in finite horizon dynamic games. The latter concept has been generalized to infinite horizon games by Asheim (1997, Definition 2). Perfectly coalition-proof equilibrium in infinite horizon games is not, however, a refinement of weak renegotiation-proofness. To our knowledge, there exists no refinement of the concept of weakly renegotiation-proof equilibrium that takes into account that also a subset of players can gain by implementing a coordinated deviation.

4.2 Related Literature on Climate Change

Proposition 1 is a "folk-theorem" result for weakly renegotiation-proof equilibria, showing that an efficient outcome can be disciplined through the threat of punishment if δ is high enough (van Damme 1989, is an early contribution of this kind in the case of weak renegotiation-proofness). It shows that a Pareto-efficient climate agreement can be implemented if $\delta \geq (n-1)/n$.

We can illustrate how a weakly renegotiation-proof equilibrium implementing a Pareto-efficient climate agreement may look like, by applying the result of Proposition 1 to a two-region world, each with $n/2$ countries. Refer to the regions as A and B. Since the total number of countries is even with two equally sized regions, we may satisfy the requirements on the subset $P_i(n)$ of countries punishing a deviating country i (namely (1) $i \notin P_i(n)$ and (2) the number of countries in $P(n)$ equals $n/2$) by having a unilateral deviation by a country in region A be punished by all countries in region B and vice versa.

This means that a unilateral deviation by a country in region A triggers a one-period reduction in abatement by all countries in region B. This inflicts an equally hard punishment on all countries in A. On the other hand, since $k = n/2 < (n+1)/2 = (s+p)/2$, it follows from Proposition 4 of the appendix that all countries in region B strictly benefit by carrying out the punishment.

This arrangement can be contrasted with that of Asheim et al. (2006), where a global weakly renegotiation-proof equilibrium is cast in terms of two regional agreements. In this equilibrium, a unilateral deviation by a country in region A triggers a one-period reduction in abatement by all the other countries in region A, and likewise in region B. Hence, the weakly renegotiation-proof equilibrium entails that the countries that benefit during the one-period punishment phase are in the same region as the deviating country, while the countries in region B are harmed twice: *both* by the initial unilateral deviation of a country in region A *and* by the subsequent punishment by the other countries in region A.

The alternative proposed in our paper has the appealing feature of inflicting the punishments within the region which is to blame for the temporary break-down of cooperation, and rewarding the innocent countries of the other region. With this set-up the countries in the same region as the deviator are harmed twice, an arrangement that might have a more disciplining effect on a potential deviator than the equilibrium proposed by Asheim et al. (2006).

In the present model with a continuum choice of abatement levels, there is full participation independently of the number of countries, provided that the discount rate is sufficiently high. So in a world with 200 countries, all 200 countries abate at the Pareto-efficient level $q^{200} = 200b/c$, *with 100 countries punishing a unilateral deviation* by reducing their abatement to $q^1 = b/c$.

In contrast, the model of Asheim et al. (2006), having a binary choice of abatement levels, leads to a fixed absolute number of participating countries. E.g., if the cost of abatement in the binary choice model is eight times each country's benefit of abatement, then the analysis of Asheim et al. (2006) yields 18 participating countries, nine countries in each region, *with eight countries punishing a deviator*, even in a world with 200 countries. With these parameter values, the result that eight countries punish carries over to the analysis of Froyn and Hovi (2008). However, by relaxing a restrictive assumption made by Asheim et al. (2006), namely that of a two-region world where all other countries in the deviator's region must punish, they are able to construct a weakly renegotiation-proof equilibrium where there is full participation.

What is the reason for this striking divergence between the binary and continuum abatement choice models? Under the parameter values of the previous paragraph, with the cost of abatement being eight times each country's benefit of abatement, punishing is at least as good as renegotiating back to cooperation only if there is at most eight punishing countries. Hence, in the binary choice model, the requirement for weak renegotiation-proofness precludes more than eight punishing countries. On the other hand, since the binary choice is fixed, each country's short-term gain from non-compliance (i.e., by not abating when specified to do so) is independent of the total number of countries. Hence, also the requirement for subgame-perfectness is unrelated to the total number of countries, leading to a fixed *absolute* number of punishing countries.

In comparison, in the continuum abatement choice model, the Pareto-efficient abatement level of each country is a linear function of the total number of countries: $q^n = nb/c$ (cf. Eq. 2). In the equilibrium of Proposition 1, this relaxes the requirement for weak renegotiation-proofness (r.h.s. of (6)), but tightens the requirement for subgame-perfectness (l.h.s. of (6)). As we have shown, with a fixed *fraction* ($\approx 1/2$) of punishing countries, both these requirements are satisfied.

This difference between the binary and continuum abatement choice models leads also to different requirements for the discount factor δ. In the binary choice model with the cost of abatement being eight times each country's benefit of abatement, Froyn and Hovi (2008) find that a Pareto-efficient agreement with 200 countries can be implemented if the discount factor exceeds 0.95; in fact, a discount factor equal to 0.95 is sufficient independently of how many countries the world consists of.

In comparison, in the continuum choice model it follows from (11) that a Pareto-efficient agreement between 200 countries can be implemented if and only if the discount factor exceeds 0.99. Moreover, by applying Proposition 2, it follows that only a shallow treaty is feasible if $\delta = 0.95$, with all 200 countries abating $q^{39} = 39b/c$ and 20 countries punishing a deviating country by reducing their abatement to $q^1 = b/c$. Hence, even though this less ambitious agreement has full participation, the resulting total abatement is less than 20% of the Pareto-efficient level.

Thus, Proposition 2 considers what can be implemented if δ is not sufficiently high, echoing the kind of analysis done by Abreu (1986, 1988), only that we here consider weakly renegotiation-proof equilibria. This problem has been mostly ignored in the literature on self-enforcing climate agreement (with Finus and Rundshagen 1998, Sect. 4, as a notable exception). In our view, the real possibility of high time discounting and long detection lags makes it a subject worthy of analysis.

To support this claim, note that the first commitment period of the Kyoto Protocol is 5 years, and the Protocol's rules for emissions accounting and reporting entail that deviations will be detected no earlier than 2–3 years after the end of the commitment period. With such considerable time lags between deviations and punishments, the relevant discount rate will be high, and under such circumstances, our analysis shows that a shallow agreement might result. More generally, our findings highlight the importance of designing a climate agreement where non-compliance is detected early and punishments are carried out promptly. The choice between agreements with quantitative restrictions vs. agreements where the parties commit to use particular policy instruments, like emission taxes, illustrate this. Our findings might serve as an argument in the favor of the latter type of agreements if these can be designed with shorter detections lags than the former.

Appendix: Proof of Theorem 1 and Proposition 2

In this appendix we characterize weak renegotiation-proofness for the simple strategy profile determined by (4) when $s > 1$ and $p \geq 0$.

Proof of Theorem 1

We first find through Proposition 3 the condition that ensures that this strategy profile is a subgame-perfect equilibrium and then proceed to provide through Proposition 4 the condition that ensures that such a subgame-perfect equilibrium is weakly renegotiation-proof. Theorem 1 is a direct consequence of Propositions 3 and 4.

Subgame-Perfectness

Let $\boldsymbol{\alpha}^s$ denote the average discounted payoff of each signatory when $\mathbf{a}^s$ is followed. Likewise, let $\boldsymbol{\pi}_i^s$ denote the average discounted payoff of a signatory i when $\mathbf{p}_i^s$ is followed.

Lemma 1 *The punishment inflicted on country i through* $\mathbf{p}_i^s$ *relative to following the agreement* $\mathbf{a}^s$ *equals*

$$\boldsymbol{\alpha}^s - \boldsymbol{\pi}_i^s = (1-\delta)(s-p)k\frac{b^2}{c}\,.$$

Proof By inserting $\mathbf{a}^s$ into (1) and (3), we obtain

$$\boldsymbol{\alpha}^s = bms\frac{b}{c} + b(n-m)\frac{b}{c} - \frac{c}{2}\left(s\frac{b}{c}\right)^2. \tag{A1}$$

By inserting $\mathbf{p}_i^s$ into (1) and (3), we obtain

$$\boldsymbol{\pi}_i^s = (1-\delta)\left(b(m-k)s\frac{b}{c} + bkp\frac{b}{c} + b(n-m)\frac{b}{c} - \frac{c}{2}\left(s\frac{b}{c}\right)^2\right) + \delta\boldsymbol{\alpha}^s\,.$$

The lemma is obtained by subtracting $\boldsymbol{\pi}_i^s$ from $\boldsymbol{\alpha}^s$. □

Lemma 1 gives the size of the future punishment inflicted on a signatory when it deviates from the simple strategy profile determined by (4). This must be compared to the short-term gain that a signatory can reap by deviating from the abatement prescribed by this strategy profile. The size of this short-term gain is provided by the following lemma.

Lemma 2 *Assume that the simple strategy profile determined by (4) prescribes the abatement* rb/c*, with* $r \geq 0$*, for country i. Then the maximal short-term gain that country i can reap through a unilateral deviation equals*

$$\frac{(r-1)^2}{2}\cdot\frac{b^2}{c}\,.$$

Proof The short-term gain of a unilateral deviation by country i does not depend on the fixed behavior of the other countries. Furthermore, independently of r and the behavior of the other countries, country i maximizes its short-term payoff by choosing $q_i = b/c$. Hence,

$$\left[b\frac{b}{c} - \frac{c}{2}\left(\frac{b}{c}\right)^2\right] - \left[br\frac{b}{c} - \frac{c}{2}\left(r\frac{b}{c}\right)^2\right] = \frac{(r-1)^2}{2}\cdot\frac{b^2}{c}$$

is the maximal short-term gain that country i can reap through a unilateral deviation. □

We can now characterize subgame-perfectness for the set of strategy profiles considered.

Proposition 3 *The simple strategy profile determined by (4) with* $s > 1$ *and* $p \geq 0$ *is a subgame-perfect equilibrium for* $\delta \in (0, 1)$ *if and only if k, s and p satisfy* $s > p$ *and*

$$\frac{1}{2\delta}\cdot\frac{(\max\{s-1, |p-1|\})^2}{s-p} \leq k\,. \tag{A2}$$

Proof *If part.* Let k, s and p satisfy $s > 1$, $p \geq 0$, $s > p$ and (A2). We only need to check for one-period deviations, since it follows from the theory of repeated games with discounting (Abreu 1988, p. 390) that a player cannot gain by a multi-period deviation if he cannot gain by some one-period deviation.

Throughout, the strategy profile prescribes that non-signatories choose b/c as their abatement level. Hence, even though any one-period deviation by a non-signatory is not punished, it follows from Lemma 1 that they have no incentive to deviate.

Signatories are prescribed to choose sb/c along $\mathbf{a}^s$. It follows from Lemmas 1 and 2 that there is no profitable deviation if

$$(1-\delta)\frac{(s-1)^2}{2}\cdot\frac{b^2}{c} \leq \delta(1-\delta)(s-p)k\frac{b^2}{c}, \tag{A3}$$

which can be rewritten as

$$\frac{1}{2\delta}\cdot\frac{(s-1)^2}{s-p} \leq k. \tag{A4}$$

The signatories (including country i itself) not inflicting punishment on country i in the first stage of $\mathbf{p}_i^s$ and all signatories in later stages of $\mathbf{p}_i^s$ are also prescribed to choose sb/c, followed by $\mathbf{p}_j^s$ if there is a unilateral deviation by a signatory j and by $\mathbf{a}^s$ if there is no such deviation. Hence, also in these cases there is no profitable deviation if (A4) is satisfied.

Finally, the signatories inflicting punishment on country i are prescribed to choose pb/c in the first stage of $\mathbf{p}_i^s$, followed by $\mathbf{p}_j^s$ if there is a unilateral deviation by a signatory j and by $\mathbf{a}^s$ if there is no such deviation. By Lemmas 1 and 2, there is no profitable deviation if

$$(1-\delta)\frac{(p-1)^2}{2}\cdot\frac{b^2}{c} \leq \delta(1-\delta)(s-p)k\frac{b^2}{c}, \tag{A5}$$

which can be rewritten as

$$\frac{1}{2\delta}\cdot\frac{(p-1)^2}{s-p} \leq k. \tag{A6}$$

Since $s > 1$, inequalities (A4) and (A6) are equivalent to inequality (A2).

Only-if part. Suppose $s \leq p$. Since $s > 1$, it follows from (A3) that there is a profitable deviation from $\mathbf{a}^s$.

Assume that $s > p$. Suppose that (A4) is not satisfied. Then it follows from (A3) that there is a profitable deviation from $\mathbf{a}^s$. Suppose that (A6) is not satisfied. Then it follows from (A5) that there is a profitable deviation from the first stage of each punishment path $\mathbf{p}_i^s$.

Since (A4) and (A6) are equivalent to (A2), we have that $s > p$ and (A2) are necessary conditions for the subgame-perfectness of the simple strategy profile determined by (4) with $s > 1$ and $p \geq 0$. □

Weak Renegotiation-Proofness

Let $\boldsymbol{\beta}_i^s$ denote the average discounted payoff of each of the signatories inflicting punishment on country i when $\mathbf{p}_i^s$ is implemented.

Proposition 4 *Assume that the simple strategy profile determined by (4) with $s > 1$ and $p \geq 0$ is a subgame-perfect equilibrium for $\delta \in (0,1)$. Then this strategy profile is weakly renegotiation-proof if and only if k, s and p satisfy*

$$k \leq \frac{1}{2}(s+p). \tag{A7}$$

Proof By the definition of weak renegotiation-proofness, we must determine when there do not exist two continuation equilibria such that all players strictly prefer the one to the other. Given the structure of the simple strategy profile determined by (4), there exist $m+1$ different continuation equilibria, implementing the play of $\mathbf{a}^s$ and $\mathbf{p}_i^j$ for all $j \in M$.

Since the strategy profile is subgame-perfect, it follows from Proposition 3 that $s > p$, implying that $\boldsymbol{\alpha}^s > \boldsymbol{\pi}_i^s$. It follows that all non-signatories as well as all signatories not inflicting punishment strictly prefer $\mathbf{a}^s$ to any punishment path $\mathbf{p}_i^s$. If $\boldsymbol{\alpha}^s > \boldsymbol{\beta}_i^s$, then all countries, including the punishing signatories, strictly prefer the continuation equilibrium in the "empty" history to the continuation equilibrium following a unilateral deviation by country i. If $\boldsymbol{\alpha}^s \leq \boldsymbol{\beta}_i^s$, then the continuation equilibrium following a unilateral deviation by country i is a best continuation equilibrium for each signatory inflicting punishment on country i and a worst continuation equilibrium for country i itself, implying that all players never strictly prefer one continuation equilibrium to another.

Hence, there do not exist two continuation equilibria such that all countries strictly prefer the one to the other if and only if

$$\boldsymbol{\beta}_i^s - \boldsymbol{\alpha}^s \geq 0\,. \tag{A8}$$

By inserting $\mathbf{p}_i^s$ into (1) and (3), it follows that

$$\boldsymbol{\beta}_i^s = (1-\delta)\left(b(m-k)s\frac{b}{c} + bkp\frac{b}{c} + b(n-m)\frac{b}{c} - \frac{c}{2}\left(p\frac{b}{c}\right)^2\right) + \delta\boldsymbol{\alpha}^s\,.$$

By comparing with (A1) we obtain

$$\boldsymbol{\beta}_i^s - \boldsymbol{\alpha}^s = (1-\delta)(s-p)\left(\tfrac{1}{2}(s+p)-k\right)\frac{b^2}{c}\,,$$

implying that (A8) is equivalent to (A7). □

Proof of Proposition 2

Assume $\delta \in \big(0, (n-1)/n\big)$, and consider the simple strategy profile determined by (4) with $s > 1$ and $p \geq 0$. We now apply Theorem 1 to find the maximum treaty depth for which this simple strategy profile is weakly renegotiation-proof, thereby proving Proposition 2. For the statement of Proposition 2 and the working of the proof below, it is helpful to note that

$$\left\{\left[\frac{k-1}{k}, \left(\frac{2k-1}{2k}\right)^2\right), \left[\left(\frac{2k-1}{2k}\right)^2, \frac{k}{k+1}\right)\right\}_{k\in\{1,\ldots,n-1\}}$$

is a partition of the interval $\big[0, (n-1)/n\big)$.

It can be checked that the functions

$$s : (0, (n-1)/n) \to \mathbb{R}_+$$
$$p : (0, (n-1)/n) \to \mathbb{R}_+$$

as given in Proposition 2 satisfy $s(\delta) \in (1, \infty)$ and $p(\delta) \in [0, 1]$ for all $\delta \in \big(0, (n-1)/n\big)$. Furthermore, $s(\delta) - 1 \geq |p(\delta) - 1|$ for all $\delta \in (0, (n-1)/n)$, since $s(\delta) = 1 + 4\delta$ and $p(\delta) = 1 - 4\delta$ for $\delta \in (0, \frac{1}{4})$ and $s(\delta) \geq 2$ for $\delta \geq \frac{1}{4}$. Hence, Theorem 1 implies that if, for every $\delta \in \big(0, (n-1)/n\big)$, $s(\delta)$ is the maximum s for which there exist $p \in [0, s)$ and $k \in \{1, \ldots, n-1\}$ satisfying (A4) and (A7), then $s(\delta)$ is the maximum s also under (5) of Theorem 1.

There are two cases to consider.

CASE A: $p \in (0, s)$. In this case, we can assume that (A7) is satisfied with equality, because otherwise (A4) could have been relaxed by reducing p. Hence, $2k = s + p$, implying that (A4) and (A7) can be rewritten as:

$$f(s; k, \delta) := s^2 - 2(1 + 2k\delta)s + (1 + 4k^2\delta) \leq 0 \quad \text{and} \quad s < 2k\,. \tag{A9}$$

The equation $f(s; k, \delta) = 0$ has a solution if and only if $(k-1)/k \leq \delta$. If $(k-1)/k \leq \delta$, then the maximum s for which $f(s; k, \delta) \leq 0$ is given by

$$s^A(k, \delta) := 1 + 2k\delta + 2\sqrt{k\delta(1 - k(1-\delta))}\,.$$

Furthermore, $s^A(k, \delta) < 2k$ is equivalent to $\delta < \big((2k-1)/2k\big)^2$. Hence, (A9) can be satisfied for a maximized value of s if and only if $(k-1)/k \leq \delta < \big((2k-1)/2k\big)^2$.

CASE B: $p = 0$. In this case, (A4) and (A7) can be rewritten as:

$$g(s; k, \delta) := s^2 - 2(1 + k\delta)s + 1 \leq 0 \quad \text{and} \quad s \geq 2k\,. \tag{A10}$$

The maximum s for which $g(s; k, \delta) \leq 0$ is given by

$$s^B(k, \delta) := 1 + k\delta + \sqrt{k\delta(2 + k\delta)}\,.$$

Furthermore, $s^B(k, \delta) \geq 2k$ is equivalent to $\big((2k-1)/2k\big)^2 \leq \delta$. Hence, (A10) can be satisfied if and only if $\big((2k-1)/2k\big)^2 \leq \delta$.

The analysis of cases A and B above has the following implications:

- If there exists $\bar{k} \in \mathbb{N}$ s.t. $\big((2\bar{k}-1)/2\bar{k}\big)^2 \leq \delta < \bar{k}/(\bar{k}+1)$, then only case B is possible. Since s^B is increasing in k, the treaty depth is maximized by choosing the largest k consistent with $\big((2k-1)/2k\big)^2 \leq \delta$, namely $k = \bar{k}$ $(\in \{1, \ldots, n-1\})$, so that $s = s^B(\bar{k}, \delta)$ and $p = 0$.
- If there exists $\bar{k} \in \mathbb{N}$ s.t. $(\bar{k}-1)/\bar{k} \leq \delta < \big((2\bar{k}-1)/2\bar{k}\big)^2$, then case A is possible with $k = \bar{k}$ and, provided $\bar{k} > 1$, case B is possible with $k < \bar{k}$. With $\bar{k} > 1$, it can be shown that, for all $\delta \in \big[(\bar{k}-1)/\bar{k}, \big((2\bar{k}-1)/2\bar{k}\big)^2\big)$ and $k < \bar{k}$, $s^A(\bar{k}, \delta) > s^B(k, \delta)$, implying that treaty depth is maximized by choosing $k = \bar{k}$ $(\in \{1, \ldots, n-1\})$, $s = s^A(\bar{k}, \delta)$, and $p = 2\bar{k} - s^A(\bar{k}, \delta)$.

By writing $s(\delta) := s^A(k, \delta)$ and $p(\delta) := 2k - s(\delta)$ if there exists $k \in \mathbb{N}$ s.t. $(k-1)/k \leq \delta < \big((2k-1)/2k\big)^2$, and $s(\delta) := s^B(k, \delta)$ and $p(\delta) = 0$ if there exists $k \in \mathbb{N}$ if there exists $k \in \mathbb{N}$ s.t. $\big((2k-1)/2k\big)^2 \leq \delta < k/(k+1)$, Proposition 2 summarizes the results given in the bullet points above.

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Essay 2
International emissions trading in a noncooperative climate policy game

Joint work with Dag Einar Sommervoll

Extended version of article published in *Economics Letters*

International emissions trading in a noncooperative climate policy game*

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...
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Abstract

Using a non cooperative climate policy game applied in the literature, we find that an agreement with international emissions trading leads to increased emissions and reduced efficiency.

Keywords: Climate change; international environmental agreements;emissions trading; non-cooperative game theory.
JEL-codes: C7, Q2,Q4

1 Introduction

Economic theory and common wisdom tell us that emissions trading may give immediate efficiency rewards as this market's invisible hand ensures that emission cuts occur where cutting costs are low. However, it complicates matters that in an international setting the initial allocation of emission quotas is not determined by nature or any supranational agency. Rather, the volume and distribution of permits must be approved by individual governments. The question we raise is whether targets will be

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set differently in anticipation of trade, and whether that would outweigh the potential gains from trade. We find that it does, giving higher global emissions and reduced efficiency compared to a game without trade.

Our analysis is based on a climate policy game which is characterized by lack of efficient bargaining when an international agreement on emission reductions is settled. We assume that the governments set their national emission targets individually based on national interests. The climate negotiations over the last years indicate that this approach is relevant. Recall, for example, that the national emission targets in the Copenhagen Accord, which have been leading in the subsequent negotiations, where quantified by individual governments *after* the Copenhagen meeting. Hence, those targets are not a result of negotiations and are therefore unlikely to maximize joint welfare, as most commonly assumed in the literature. Closely related literature includes Cramton and Stoft (2010a, 2010b), Godal and Holtsmark (2011), and MacKenzie (2011). Our result contrasts with Carbone et al. (2009), and we extend the climate policy game found in Helm (2003).[1]

The next section presents the theoretical model and our result. The subsequent section concludes. The proof of our result can be found in Appendix A.

2 Analysis

There is a set of countries $I = \{1, ..., n\}$. Each country $i \in I$ is composed of a government and m_i firms. Each firm has quadratic abatement costs

$$c_{ji}\left(a_{ji}\right) = \frac{\gamma}{2} a_{ji}^2, \tag{1}$$

where γ is a positive parameter and a_{ji} is the abatement carried out by firm j in country i. If abatement is carried out efficiently within each country, country i has abatement cost functions that could be written in the conventional quadratic format:

$$c_i(a_i) = \min_{a_{ji},\ j=\in\{1,\dots,m_i\}} \left(\sum_{j=1}^{m_i} \frac{\gamma}{2} a_{ji}^2 \right) = \frac{\sigma_i}{2} a_i^2, \tag{2}$$

where a_i is total abatement in country i and $\sigma_i := \gamma / m_i$. The countries experience linear benefits from global emission abatement $b_i \cdot \left(\sum_{i \in I} a_i\right)$,

[1]For an overview of other relevant literature, see Finus (2008).

where b_i is a parameter. As benefits from global emission abatement is a public good, we assume that b_i is proportional to the size of economy i, reflected by the numbers of firms m_i. Hence, $b_i = \beta m_i$, for all $i \in I$, where β is a positive parameter.

Our main focus is on the following two-stage game, named the *game with permit trading* (superscript T is used to indicate the solution to this game):

Stage 1: Each government chooses its initial endowment of emissions permits ω_i (emission target, for shor) . The permits are transferred to the firms.
Stage 2: Firms, which all have access to an international permit market where the unit price is p, select their level of abatement a_{ji}.

Note that even though we presume that all governments play individually and noncooperatively against all other governments, some items must still be negotiated and agreed upon. In particular, governments must agree that permits issued in any country are recognized as documents suitable for compliance in their own country. It is also assumed that governments comply with their obligations by enforcing firms to fully match their emissions with their corresponding number of permits.

We start with **stage 2** of the game. Abatement a_i in country $i \in I$ is determined such that each firm is maximizing its net income from permit sales minus its abatement costs. It follows that a_i satisfies

$$\frac{\partial c_i\left(a_i\right)}{\partial a_i} = p \ , \tag{3}$$

and the firms' marginal abatement costs will be equalized. Hence, there will be an efficient allocation of abatement efforts both within and across countries.

At **stage 1** each government $i \in I$ maximizes national welfare $\pi_i\left(\omega\right)$ with respect to ω_i, where

$$\pi_i\left(\omega\right) := b_i \sum_{j \in I} a_j\left(\omega\right) - \frac{\sigma_i}{2} a_i^2 + p\left(\omega\right)\left(\omega_i - \bar{e}_i + a_i\left(\omega\right)\right).$$

Hence, a Nash equilibrium is characterized by the first-order conditions

$$b_i \cdot \sum_{j \in I} \frac{\partial a_j}{\partial \omega_i} - c_i' \left(a_i \left(\omega\right)\right) \cdot \frac{\partial a_i}{\partial \omega_i} + \frac{\partial p}{\partial \omega_i} \left(\omega_i - \bar{e}_i + a_i \left(\omega\right)\right) + p \left(1 + \frac{\partial a_i}{\partial \omega_i}\right) = 0, \tag{4}$$

for all $i \in I$.

Next, sum the left hand side of (4) for all $i \in I$, taking into account that the price effect of increased supply of permits is the same irrespective of the additional permits' country of origin and that $\sum_{i \in I} \left(\omega_i - \bar{e}_i + a_i \left(\omega\right)\right) = 0$ as well as the first order condition (3). Then we have that

$$p = \bar{b}, \tag{5}$$

where $\bar{b} = (1/n) \sum_{j \in I} b_j$, see also MacKenzie (2011).

Using that $\sigma_i = \gamma / m_i$ as well as (2) and (3), we have that

$$a_i^T = \frac{m_i}{\gamma} p \tag{6}$$

for all $i \in I$. Define $\mathbf{m} := \{m_1, ..., m_n\}$ and $M := \sum_{i \in I} m_i$. Note that (5) means that $p = (\beta / n) \sum m_i$. Thus, we have that

$$a_i^T = \frac{m_i}{\gamma} \frac{\beta}{n} M. \tag{7}$$

Global abatement follows:

$$a^T \left(\mathbf{m}\right) = \frac{\beta}{\gamma} \frac{1}{n} M^2. \tag{8}$$

Let $\bar{e}_i$ be the business–as–usual emissions of country i and $\omega := (\omega_1, ..., \omega_n)$ a profile of targets. Then ω and the market-clearing condition

$$\sum_{i \in I} \left(\bar{e}_i - a_i\right) = \sum_{i \in I} \omega_i \tag{9}$$

determine a unique equilibrium permit price $p\left(\omega\right) > 0$. Furthermore, from (6), this in turn determines the abatement $a_i\left(\omega\right)$ for all $i \in I$.

From the above results we have that global welfare in the equilibrium of the game described above is given by:

$$\pi^T \left(\mathbf{m}\right) = \frac{\beta^2}{\gamma} \left(\frac{n - \frac{1}{2}}{n^2}\right) M^3, \tag{10}$$

where $\pi^T := \sum_{i \in N} \pi_i^T$.

For comparison only, we next define a game of reference, labeled the *game without trade* (superscript N is used to indicate the solution to this game). This game follows the same procedure as of the game described above, with the exception that there is no international permit market. Hence, at the second stage of the game firms set their abatement levels such that $a_i^N = \omega_i^N$. At the first stage of the game the governments set their target ω_i to the level which maximizes $b_i \left(\sum_{i \in N} a_i\right) - c_i (a_i)$. Hence, the abatement levels become:

$$a_i^N = \frac{b_i}{\sigma_i}. \tag{11}$$

It follows that global emission abatement and welfare in the equilibrium of this game are:

$$a^N (\mathbf{m}) = \frac{\beta}{\gamma} \sum_{i \in I} m_i^2, \tag{12}$$

$$\pi^N (\mathbf{m}) = \frac{\beta^2}{\gamma} \left(M \left(\sum_{j=1}^{n} m_j^2 \right) - \frac{1}{2} \sum_{j=1}^{n} m_j^3 \right). \tag{13}$$

Our main result follows:

Proposition 1 *If there exists at least one pair* (i, j) *such that* $m_i \neq m_j$, $i,\, j \in I$, *then we have that*

$$a^N (\mathbf{m}) > a^T (\mathbf{m}),$$
$$\pi^N (\mathbf{m}) > \pi^T (\mathbf{m}).$$

.

Proof. See Appendix A.

Proposition 1 states that trade reduces efficiency and increases emissions. Certain intuitive conclusions flow from this result. In the game with trading, firms choose their emissions levels such that marginal abatement costs $c_i' (a_i)$ equal the international permit price $p = \bar{b}$. For instance, in the case of a large economy (above average number of firms) we have that $b_i > p = \bar{b}$, and this country will end up as a permit importer and $c_i' (a_i) < b_i$. Without trade we have that $c_i' (a_i) = b_i$. Hence, this country will reduce its abatement as trading is introduced. Correspondingly, small economies increase their abatement due to trade. Moreover, it follows from (2) and the definition of σ_i that small economies have steeper marginal abatement cost functions compared to larger economies, and consequently a large economy must therefore carry out a larger downward adjustment of its abatement level than small economies must adjust their abatement upwards. It follows that $a^N(\mathbf{m}) > a^T(\mathbf{m})$.

The intuition behind the result that $\pi^N(\mathbf{m}) > \pi^T(\mathbf{m})$ is more straightforward. In a non-cooperative equilibrium, global abatement is inefficiently low. International emissions trading will lead to even lower total abatement. Hence, emissions trading on the one hand gives an efficiency gain due to efficient cross-border abatement allocation, but on the other an inefficiently low abatement level is further reduced and this last effect dominates.

3 Concluding remarks

The world community is struggling to come together and negotiate an effective and ambitious climate agreement. The process for determining national emission quotas in the most recent agreements does not resemble efficient bargaining, and is possibly closer to a formalization of a classical noncooperative equilibrium. In this paper we have shown that within a simple climate policy game, emissions trading in this situation leads to increased emissions and reduced efficiency.

A Appendix

Proof. Proposition 1 claims that if there exists an i and j, such that $m_i \neq m_j$, i, $j \in N$, then

$$a^N(\mathbf{m}) > a^T(\mathbf{m}), \tag{A.1}$$

$$\pi^N(\mathbf{m}) > \pi^T(\mathbf{m}). \tag{A.2}$$

where we use $\mathbf{m} := \{m_1, ..., m_n\}$. In order to prove this, define a vector $\acute{\mathbf{m}}$ with n identical elements $\acute{m} = M/n$

$$\acute{\mathbf{m}} := \{\underbrace{\acute{m}, ..., \acute{m}}_{n \text{ elements}}\}. \tag{A.3}$$

It follows from (8), (10), (12) and (13) that

$$a^N(\acute{\mathbf{m}}) = a^T(\acute{\mathbf{m}}) = a^T(\mathbf{m}), \tag{A.4}$$

$$\pi^N(\acute{\mathbf{m}}) = \pi^T(\acute{\mathbf{m}}) = \pi^T(\mathbf{m}). \tag{A.5}$$

It follows that if

$$a^N(\mathbf{m}) > a^N(\acute{\mathbf{m}}), \tag{A.6}$$

$$\pi^N(\mathbf{m}) > \pi^N(\acute{\mathbf{m}}), \tag{A.7}$$

then (A.1) and (A.2) apply. In the following we will therefore show that (A.6) and (A.7) apply. Firstly, define

$$\bar{m}_k := \frac{1}{k}\sum_{j=1}^{k} m_j,\ \ k = 1, ..., n,$$

which is the basic building block in a set of $n-$element vectors $\bar{\mathbf{m}}_k$, $k \in \{1, ..., n\}$, where the first k elements are equal to the average size of $m_1, ..., m_k$ in the vector $\mathbf{m}$ such that

$$\bar{\mathbf{m}}_k := \{\underbrace{\bar{m}_k, ..., \bar{m}_k,}_{k\text{ elements}} m_{k+1}, ..., m_n\}.$$

Note that $\bar{\mathbf{m}}_1 = \mathbf{m}$ and $\bar{\mathbf{m}}_n = \acute{\mathbf{m}}$. In order to show that (A.6) and (A.7) apply, we will prove that we have two chains of inequalities where

$$a^N(\mathbf{m}) \geq a^N(\bar{\mathbf{m}}_2) \geq\ ...\ \geq a^N(\bar{\mathbf{m}}_{n-1}) \geq a^N(\acute{\mathbf{m}}), \tag{A.8}$$

$$\pi^N(\mathbf{m}) \geq \pi^N(\bar{\mathbf{m}}_2) \geq\ ...\ \geq \pi^N(\bar{\mathbf{m}}_{n-1}) \geq \pi^N(\acute{\mathbf{m}}), \tag{A.9}$$

and that if there exists at least one pair (i, j) such that $m_i \neq m_j$, then at least one of the inequalities in each of these two chains is strict. Consider firstly inequality number k in (A.8). We have

$$a^N(\bar{\mathbf{m}}_k) = \frac{\beta}{\gamma}\left(k\bar{m}_k^2 + m_{k+1}^2 + \sum_{j=k+2}^{n} m_j^2\right), \tag{A.10}$$

$$a^N(\bar{\mathbf{m}}_{k+1}) = \frac{\beta}{\gamma}\left((k+1)\,\bar{m}_{k+1}^2 + \sum_{j=k+2}^{n} m_j^2\right). \tag{A.11}$$

Subtracting the expression in (A.10) from the expression in (A.11) gives that

$$\begin{aligned} a^N(\bar{\mathbf{m}}_k) - a^N(\bar{\mathbf{m}}_{k+1}) &= \frac{\beta}{\gamma}\left(k\bar{m}_k^2 + m_{k+1}^2 + \sum_{j=k+2}^{n} m_j^2\right) \\ &- \frac{\beta}{\gamma}\left((k+1)\,\bar{m}_{k+1}^2 + \sum_{j=k+2}^{n} m_j^2\right), \end{aligned}$$

which could be reformulated to

$$\frac{\beta}{\gamma}\left(k\bar{m}_k^2 + m_{k+1}^2 + \sum_{j=k+2}^{n} m_j^2 - (k+1)\,\bar{m}_{k+1}^2 - \sum_{j=k+2}^{n} m_j^2\right).$$

Hence, we have that

$$a^N(\bar{\mathbf{m}}_k) - a^N(\bar{\mathbf{m}}_{k+1}) = \frac{\beta}{\gamma}\left(k\bar{m}_k^2 + m_{k+1}^2 - (k+1)\,\bar{m}_{k+1}^2\right).$$

Recall that we have:

$$\bar{m}_{k+1} = \frac{1}{k+1}\sum_{j=1}^{k} m_j + \frac{1}{k+1} m_{k+1},$$

which gives that

$$\bar{m}_{k+1} = \frac{1}{k+1}\left(k\bar{m}_k + m_{k+1}\right).$$

Hence, we have that:

$$a^N(\bar{\mathbf{m}}_k) - a^N(\bar{\mathbf{m}}_{k+1}) = \frac{\beta}{\gamma}\left(k\bar{m}_k^2 + m_{k+1}^2 - \frac{1}{k+1}\left(\left(k\bar{m}_k + m_{k+1}\right)\right)^2\right),$$

which gives:

$$a^N(\bar{\mathbf{m}}_k) - a^N(\bar{\mathbf{m}}_{k+1}) = \frac{\beta}{\gamma}\frac{k}{k+1}\left(m_{k+1} - \bar{m}_k\right)^2. \tag{A.12}$$

Hence, we have shown that $a^N(\bar{\mathbf{m}}_k) \geq a^N(\bar{\mathbf{m}}_{k+1})$ for any $k \in \{1, ..., n\}$ and the inequality is strict if $m_{k+1} \neq \bar{m}_k$. Therefore, all inequalities in (A.8) apply, and because we assume there exists an i and j, such that $m_i \neq m_j$, i, $j \in N$, then (A.1) applies.

Next, we will show that (A.2) applies. Define $M_k := \sum_{i=1}^{k} m_i$. It follows from (13) and the definitions above that

$$\pi^N(\bar{\mathbf{m}}_k) = \frac{\beta^2}{\gamma}\left(M_{k+1}\left(k\bar{m}_k^2 + m_{k+1}^2\right) - \frac{1}{2}\left(k\bar{m}_k^3 + m_{k+1}^3\right)\right) + \sum_{j=k+2}^{n} \pi_j^N(\bar{\mathbf{m}}_k),$$

$$\pi^N(\bar{\mathbf{m}}_{k+1}) = \frac{\beta^2}{\gamma}\left(M_{k+1}(k+1)\,\bar{m}_{k+1}^2 - \frac{1}{2}(k+1)\,\bar{m}_{k+1}^3\right) + \sum_{j=k+2}^{n} \pi_j^N(\bar{\mathbf{m}}_{k+1}),$$

Using a similar procedure as used when finding (A.12), it is possible to show that

$$\pi^N(\bar{\mathbf{m}}_k) - \pi^N(\bar{\mathbf{m}}_{k-1}) = \frac{\beta^2}{\gamma}\frac{k}{2(k+1)^2}(\bar{m}_k - m_{k+1})^2 \cdot (kM_{k+1} + (k-1)(k+1)\bar{m}_k) + \left[\sum_{j=k+2}^{n}\left(\pi_j^N(\bar{\mathbf{m}}_k) - \pi_j^N(\bar{\mathbf{m}}_{k+1})\right)\right]. \tag{A.13}$$

The square bracket is non-negative because (A.8) says that $a^N(\bar{\mathbf{m}}_k) \geq a^N(\bar{\mathbf{m}}_{k+1})$, which means that countries $k+2, ..., n$ will collect at least as large payoffs in the case with $\bar{\mathbf{m}}_k$ as with $\bar{\mathbf{m}}_{k+1}$. The rest of the right hand side of (A.13) is non-negative if $n > 2$, and strictly positive if $\bar{m}_k \neq m_{k+1}$. It follows that the inequality $\pi^N(\bar{\mathbf{m}}_k) \geq \pi^N(\bar{\mathbf{m}}_{k+1})$ applies, and is strict if $\bar{m}_k \neq m_{k+1}$.

The corresponding argument applies to all the inequalities in (A.9)). Hence, we have proven that (A.7) is true, which means that (A.2) is true as well. ■

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Essay 3
Permit Trading: Merely an Efficiency-Neutral Redistribution away from Climate-Change Victims?

Joint work with Odd Godal

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Permit Trading: Merely an Efficiency-Neutral Redistribution away from Climate-Change Victims?*

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Abstract

In this paper, we present a climate-policy game with international emissions trading, where governments first select their amounts of emissions permits. These permits are transferred to firms, and then traded competitively on an international market. Compared with a game without trading, we find that the potential efficiency gains from permit trading, which have been identified in other studies, are totally undone if governments also employ a tax or subsidy on domestic emissions. The only effect of permit trading in this case is a redistribution of income away from those most affected by climate change.

Keywords: International environmental agreements; emissions trading; endogenous endowments; emissions taxes

JEL classification: *C*72; *D*62; *Q*54

I. Introduction

So far, more than 15 years of international climate talks have not resulted in any binding agreement with regards to broad participation and substantial emissions reductions. The Kyoto Protocol and Copenhagen Accord are examples par excellence of these inadequacies. Nevertheless, despite the notable absence of efficient cooperation, many measures aimed at mitigating emissions have been adopted. The purpose of this paper, which builds on the analysis by Helm (2003), is to examine some possible consequences

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of international emissions trading in a non-cooperative setting without efficient bargaining.[1]

Our point of departure (called policy A) is the classical case, where governments decide voluntarily on their emissions levels without any subsequent trade. If they follow only their own interests, and if we abstract from problems of carbon leakage, the marginal benefit of domestic emissions becomes equal to the domestic marginal climate cost of aggregate emissions.

If countries are differently affected by climate change, policy A will lead to differences in marginal abatement costs between countries. To eliminate this source of inefficiency, one could combine an international emissions trading system (policy B) with policy A. Clearly, if countries' initial endowments of allowances (targets, for short) were fixed at the emissions levels of policy A, trading would yield overall efficiency gains, to nobody's detriment. However, we assume that governments anticipate subsequent trade when targets are set. This creates incentives that are absent under policy A. That is, the establishment of a permit market when targets are endogenous generates prospects for revenues, albeit at a decreasing rate.

When studying policies A and B, Helm (2003) shows that less environmentally affected countries tend to choose less stringent targets and become permit exporters. Conversely, countries more interested in global emissions reductions access inexpensive abatement abroad; they choose more ambitious targets and become permit importers. The total effect on global emissions compared with policy A becomes ambiguous (i.e., parameter dependent; see Helm, 2003).[2] This also applies to aggregate welfare. However, in a computable general equilibrium environment, Carbone *et al.* (2009) identify substantial emissions reductions and welfare gains when policy B is combined with policy A.

In practice, the effective price of carbon is determined not only by the permit price. For instance, fossil-fuel taxes or subsidies, which are in widespread use, might come into play. Such instruments, which might be present for a variety of reasons, are absent from the analysis by Helm (2003), and they are exogenous in Carbone *et al.* (2009). The contribution of our analysis is to make these policies part of the game, that is, to combine domestic emissions taxes or subsidies (policy C) with policies A and B.[3] Under the assumption that governments set targets and choose taxes/subsidies simultaneously and non-cooperatively before

[1] The line of research to which this paper belongs is somewhat different from the more standard one on international environmental agreements; see Section IV for details.

[2] In Section III, we offer a simple example where emissions decrease.

[3] We do not model the energy markets. Nevertheless, as long as carbon emissions are proportional to fossil-fuel consumption, emissions and energy taxes (or subsidies) remain much the same.

competitive permit trading takes place internationally, the analysis of this paper shows that the resulting profile of emissions of the combined policies A, B, and C is identical to that of policy A alone. This means that the possibility of adjusting taxes and subsidies will totally undo any potential efficiency gains from international emissions trading, even though the permit market might flourish.

There are, however, distributional consequences of combining policies B and C with policy A. Countries with a low domestic marginal climate cost of aggregate emissions will have lower emissions than targets; they become permit exporters, and by receiving the associated revenues, they win. Conversely, countries with a high domestic marginal climate cost become permit importers, and lose. This also means that within the structure of the model, one cannot reach agreement on international emissions trading, except for the irrelevant symmetrical case.

These results are presented in the following. To illustrate, a two-country example appears in Section III. Section IV contains bibliographic remarks, while Section V concludes.

II. Analysis

The underlying fundamentals of our economy are identical to those in Helm (2003). There is a fixed and finite set of countries $I = \{1, \ldots, n\}$. Each country $i \in I$ is composed of a government and many price-taking firms, which have a total benefit $\pi_i(e_i)$ from releasing $e_i \geq 0$ units of emissions. Moreover, each country is adversely affected by global emissions via climate change $v_i(\sum_{j \in I} e_j)$.

We consider the following two-stage game, which we call a voluntary-emissions game with international permit trading and domestic taxation (policies A, B, and C).

Stage 1: Each government chooses both an emissions tax t_i and a target ω_i (its initial endowment of emissions permits). These permits are transferred to the firms.

Stage 2: Firms, which all have access to an international permit market where the unit price is p, select their level of emissions e_i. The firms' cost of emitting one more unit equals $p + t_i$.[4]

It is assumed that the choice variables ω_i and t_i are both free. Should ω_i be negative, then more permits must be bought than the emissions that could occur. A subsidy is nothing but a negative tax and is simply referred to as a tax (unless ambiguity arises). We also assume that governments are

[4] Alternative formulations of the game are discussed in our concluding remarks.

indifferent to whether income accrues to themselves or to domestic firms. This means, in particular, that it does not matter how emissions permits are transferred to firms (i.e., whether they are sold or allocated free of charge).

Let $\boldsymbol{\omega} := (\omega_1, \ldots, \omega_n)$ be a profile of targets and let $\mathbf{t} := (t_1, \ldots, t_n)$ be a profile of taxes. It is essential for the analysis that for every possible pair of profiles $(\boldsymbol{\omega}, \mathbf{t})$ we have a unique equilibrium at stage 2, preferably in the interior. To ensure this, we invoke the assumption that $\pi_i : \mathbb{R}_+ \to \mathbb{R}$ is twice continuously differentiable with $\pi_i'(e_i) > 0$ and $\pi_i''(e_i) < 0$, as well as $\pi_i'(e_i) \to \infty$ as $e_i \to 0$ and $\pi_i'(e_i) \to 0$ as $e_i \to \infty$.

Before we embark on the analysis of the game, we emphasize that even though we presume that all governments play individually and non-cooperatively against all other governments, some items must still be negotiated and agreed upon. In particular, governments must agree that permits issued in any country are recognized as documents suitable for compliance in any other country. That is, permits are seen as an homogeneous good. It is also assumed that governments comply with their obligations by enforcing firms to fully match their emissions with a corresponding number of permits.

We start by analyzing stage 2 of the game. Emissions e_i in country $i \in I$ are determined as if a representative national firm were maximizing $\pi_i(e_i) - (p + t_i)e_i + p\omega_i$, where the last term might vanish if permits are auctioned. Whenever $(p + t_i) > 0$, it follows that e_i satisfies

$$\pi_i'(e_i) = p + t_i \quad \text{for all} \quad i \in I, \tag{1}$$

while $e_i = \infty$ otherwise.

For any given $\mathbf{t}$, the first-order conditions (1) imply that aggregate permit demand, $\sum_{j \in I} e_j$, is a strictly decreasing function of p, which approaches 0 as $p \to \infty$ and ∞ as $p \to -\min_{j \in I} t_j$. Hence, if $\sum_{j \in I} \omega_j > 0$, then $(\boldsymbol{\omega}, \mathbf{t})$ and the market-clearing condition

$$\sum_{j \in I} e_j = \sum_{j \in I} \omega_j \tag{2}$$

determine a unique equilibrium permit price $p(\boldsymbol{\omega}, \mathbf{t}) > -\min_{j \in I} t_j$. Furthermore, from equation (1), this in turn determines the emissions $e_i(\boldsymbol{\omega}, \mathbf{t})$, which become strictly positive in all countries. If, in contrast, $\sum_{j \in I} \omega_j \leq 0$, then emissions and permit trading both vanish.

We write

$$s_i := \frac{1}{\pi_i''(e_i)} < 0 \quad \text{and} \quad S := \sum_{j \in I} s_j < s_i, \tag{3}$$

evaluated at equilibrium emissions. The following claims, which are proved in Appendix A, are applied to sort out later results.

Lemma 1 (Comparative statics). *Suppose* $\sum_{j \in I} \omega_j > 0$. *Then, under the assumed conditions for the functions* π_i, $i \in I$, *we have*

$$\frac{\partial p}{\partial \omega_i} = \frac{1}{S} < 0, \quad \frac{\partial e_i}{\partial \omega_i} = \frac{s_i}{S} \in (0, 1), \tag{4}$$

$$\frac{\partial p}{\partial t_i} = -\frac{s_i}{S} \in (-1, 0), \quad \frac{\partial e_j}{\partial t_i} = -\frac{s_i s_j}{S} > 0 \text{ if } j \neq i, \quad \frac{\partial e_i}{\partial t_i} = -\frac{s_i^2}{S} + s_i < 0, \tag{5}$$

$$\sum_{j \in I} \frac{\partial e_j}{\partial \omega_i} = 1, \quad \text{and} \quad \sum_{j \in I} \frac{\partial e_j}{\partial t_i} = 0. \tag{6}$$

Although the economic content and the ideas behind each result in equations (4)–(6) confirm the established body of literature on endowment manipulation in exchange economies and tariff retaliation in international economies, it is notable that $\partial e_i / \partial \omega_i$ is exactly the same as $-\partial p / \partial t_i$. This is so even though the first object deals with relative quantity changes, while the second concerns relative price effects. Next, we explain why this holds true, and we start with the interpretation of s_i. *Ceteris paribus*, a "large" economy, which can spread out abatement among many economic activities, will typically have a relatively slowly decreasing marginal benefit function (i.e., $|\pi_i''(e_i)|$ will be smaller than that of a "small" economy). Therefore, using definition (3), it follows that s_i / S is an indicator of the relative economic size of country i. As such, it is reasonable that a perturbation in total permit supply will be absorbed by a large economy to a greater extent than by a small economy (i.e., that $\partial e_i / \partial \omega_i$ will be proportional to s_i). Similarly, a tax increase in a large economy will, when keeping the permit price fixed, have a more substantial effect on the demand for emissions compared with the effect of a tax increase in a small economy. Thus, the imbalance in the market that a tax increase will cause becomes greater, the larger the economy is. Therefore, when the permit price must ultimately equilibrate demand with supply, the resulting price reduction will increase with the relative economic size of country i.[5]

Note that even though the emissions in country i, as a function of the variables chosen at stage 1, depend on the whole profile $(\boldsymbol{\omega}, \mathbf{t})$ of targets and emissions taxes, the decisions by firms depend solely on the international permit price and the national emissions tax t_i.

[5] Those readers interested in more general comparative statics results when utility is transferable, as it is here, can consult Flåm *et al.* (2008).

We are now prepared for the analysis of the game at stage 1. There, each government $i \in I$ maximizes $W_i(\boldsymbol{\omega}, \mathbf{t})$ with respect to (ω_i, t_i), where

$$W_i(\boldsymbol{\omega}, \mathbf{t}) := \pi_i(e_i(\boldsymbol{\omega}, \mathbf{t})) - v_i\left(\sum_{j\in I} e_j(\boldsymbol{\omega}, \mathbf{t})\right) + p(\boldsymbol{\omega}, \mathbf{t})[\omega_i - e_i(\boldsymbol{\omega}, \mathbf{t})],$$

whenever $\sum_{j\in I} \omega_j > 0$, and $W_i(\omega, \mathbf{t}) := \pi_i(0) - v_i(0)$ otherwise. So, the function W_i is well defined for all pairs of profiles $(\boldsymbol{\omega}, \mathbf{t})$.

Next, we assume that the damage function $v_i : \mathbb{R}_+ \to \mathbb{R}$ is twice continuously differentiable with $v_i'(\cdot) > 0$ and $v_i''(\cdot) \geq 0$. Together with the assumptions made on π_i, this yields the result that a Nash equilibrium, if it exists, is characterized by the first-order conditions

$$\pi_i' \cdot \frac{\partial e_i}{\partial \omega_i} - v_i' \cdot \sum_{j\in I} \frac{\partial e_j}{\partial \omega_i} + \frac{\partial p}{\partial \omega_i}(\omega_i - e_i) + p\left(1 - \frac{\partial e_i}{\partial \omega_i}\right) = 0 \qquad (7)$$

and

$$\pi_i' \cdot \frac{\partial e_i}{\partial t_i} - v_i' \cdot \sum_{j\in I} \frac{\partial e_j}{\partial t_i} + \frac{\partial p}{\partial t_i}(\omega_i - e_i) + p\left(0 - \frac{\partial e_i}{\partial t_i}\right) = 0 \qquad (8)$$

for all $i \in I$, together with equations (1) and (2) and the results in Lemma 1. In equations (7) and (8), and what follows from these, the dependence of e_i and p on $(\boldsymbol{\omega}, \mathbf{t})$, the dependence of π_i' on e_i, and the dependence of v_i' on $\sum_{j\in I} e_j$ have been suppressed. Moreover, even though there is no equilibrium with $\sum_{j\in I} \omega_j \leq 0$, it might well be that $\omega_i < 0$ for some $i \in I$.

Before presenting our main result, for comparison, we describe two games of reference. We call the first a voluntary-emissions game, where there is no permit trading, referred to as policy A in Section I. In this game, each government implements measures to maximize $\pi_i(e_i) - v_i(\sum_{j\in I} e_j)$ with respect to $e_i \geq 0$. We assume that this game has a unique Nash equilibrium. With the assumptions made on the functions π_i and v_i, it follows that $e_i > 0$ for all $i \in I$ in equilibrium, therefore satisfying

$$\pi_i'(e_i) - v_i'\left(\sum_{j\in I} e_j\right) = 0, \qquad (9)$$

for all $i \in I$.

The second game of reference combines policy A with trade; it is called a voluntary-emissions game with international permit trading (referred to as policies A and B in Section I). This is the game studied by Helm (2003) and it is a special case of our game, obtained by fixing $t_i = 0$ for all $i \in I$ and by removing it as a decision variable in stage 1. Together with market clearing, and the condition that $\pi_i'(e_i) = p$ for all firms, an equilibrium profile $\boldsymbol{\omega}$ of this game satisfies

$$\pi_i'(e_i) - v_i'(\cdot) + \frac{\partial p}{\partial \omega_i}(\omega_i - e_i) = 0 \tag{10}$$

for all $i \in I$ (see Helm, 2003, p. 2741).

In preparation for our main result, we summarize our assumptions.

Assumption 1. *The functions π_i and v_i satisfy all the aforementioned conditions.*

Assumption 2. *There exists a unique Nash equilibrium in both the voluntary-emissions game and the voluntary-emissions game with international permit trading and domestic taxation.*

By making use of Lemma 1, it turns out that equations (7) and (8) reduce to equation (9), i.e., the following result (see Appendix B for a proof).

Proposition 1 (On efficiency). *Given Assumptions 1 and 2, it follows that the equilibrium in the voluntary-emissions game with international permit trading and domestic taxation (policies A, B, and C) leads to the same emissions profile $(e_1, \ldots, e_n)$ as in the voluntary-emissions game (policy A).*

In other words, the allocation of abatement efforts and climate damages with all policies combined is exactly the same as with policy A alone. This result implies that any efficiency gains associated with combining policy B with policy A are totally undone if countries are free to tax or subsidize domestic emissions, as when policies A, B, and C are combined.[6]

To describe the key mechanism leading to the result, it is best to take the voluntary-emissions game with international permit trading (policies A and B) as a point of departure. In that game, where taxes are absent, firms chose their emissions levels such that marginal benefits equal the international permit price p. Hence, if countries have different marginal damages of aggregate emissions, the countries would face an after-trade situation where the marginal benefits of emissions $\pi_i'(e_i)$ differ from the marginal damages $v_i'(\cdot)$, see also equation (10).

Now, take for instance a permit importer who will end up with $\pi_i'(e_i) < v_i'(\cdot)$ under policies A and B. Clearly, such a country would have an interest in reducing its emissions further. However, the only way to accomplish this when the tax instrument is unavailable is for the government to

[6] Proposition 1 presumes that all governments behave consistently with fully recognizing how the choices of taxes and targets affect the international permit price. Alternatively, we could have assumed that governments (some or all) behave as price-takers in not recognizing such effects. In a previous version of this paper, we have shown that the result is robust against this alternative assumption (see Godal and Holtsmark, 2010, their Proposition 1).

select a lower target ω_i in the first stage of the game. The reason this does not pay off is that the permit price will rise; and because the country is a permit importer, market expenses will also rise. Hence, in this regime, the government of a permit-importing country is confronted with a trade-off between improving the environment and keeping the permit price low. A similar, yet opposite, trade-off holds for a permit exporter. In both cases, governments must choose an ω_i that represents a compromise between considerations of environmental quality and market revenues/expenses.

Consider next the possibility of using the tax/subsidy instrument (i.e., policies A, B, and C). Because the global emissions are determined by the total amount of permits, the choice of t_i does not influence environmental quality for a given $\boldsymbol{\omega}$. This makes it possible to dedicate the tax instrument to the terms-of-trade effects, while choosing ω_i based on environmental considerations. In short, the trade-off between achieving the desired environmental quality without adversely affecting revenues (or expenses) in the permit market, identified under policies A and B, disappears when governments also have the tax instrument available. This describes the essential mechanism leading to Proposition 1.

Because of the specific nature of this result, we might perhaps wonder whether there will be any trade in an equilibrium of our game. To address this, we combine equation (7) with equations (4) and (6) and Proposition 1, to obtain

$$(p - v_i') \cdot \left(1 - \frac{s_i}{S}\right) = -\frac{1}{S}(\omega_i - e_i). \tag{11}$$

Suppose now that there is no trade (i.e., that $e_i = \omega_i$ for all $i \in I$). Using equation (11), this gives $v_i'(\cdot) = p$ for all $i \in I$. If marginal damages in equilibrium are different for at least one distinct pair i, j, then we obtain an impossibility, implying that there must be trade.

Another direct implication of equation (11) and Proposition 1 is the following.

Proposition 2 (On distributional effects). *Given Assumptions 1 and 2, it follows that combining domestic taxation and international permit trading (policies B and C) with a voluntary-emissions game (policy A) is to the advantage of countries with low domestic marginal climate costs and to the disadvantage of countries with high domestic marginal climate costs.*

The idea behind this result is discussed next. We have already established by Proposition 1 that the emissions benefits and climate-damage costs, which a country incurs under policies A, B, and C, are identical to those incurred under policy A alone. Hence, the only difference between the two policy combinations is the flows of permits and money in the market. Now, because the domestic marginal climate cost of aggregate emissions is the cost of supplying permits, while the common permit price is the associated benefit, countries with low domestic marginal climate costs have a comparative advantage in supplying permits. Such countries become permit exporters, and (compared with policy A) they win. Victims of climate change import permits and lose.[7]

It must be emphasized, however, that a country's marginal damage cost is not merely a statement about its vulnerability to climate change, say on a per capita basis. To illustrate why, suppose that two identical countries decide to form a union. Then, the marginal climate cost for the region as a whole will typically double as a consequence of aggregation. Thus, it might well be that a small country is heavily affected by climate change for each of its citizens. However, it might be that there are so few citizens that, when adding the marginal damages up, the number is still small. As such, Proposition 2 indicates that combining policies B and C with policy A is to the disadvantage of "large" countries, while "small" countries benefit.

Propositions 1 and 2 also imply that if we were to add a market-participation stage to the game before stage 1, similar to Carbone *et al.* (2009) and Helm (2003), it follows that any participating country, which might become a permit importer, would be better off opting out of the market. Therefore, if a market-participation stage is included in the game prior to stage 1, there will be no equilibrium with participation and trade.

III. Example

To illustrate and to offer further intuitions, in this section we present a two-country example, where marginal benefits are given by $\pi'_1(e_1) = \max\{10 - e_1,\ 0\}$ and $\pi'_2(e_2) = \max\{10 - 2e_2,\ 0\}$, and marginal damage costs are $v'_1(e_1 + e_2) = 2$ and $v'_2(e_1 + e_2) = 6$. Total benefits and costs are normalized to zero when emissions are nil. The outcomes of the various policy combinations are given in Table 1.

The example illustrates that, with the chosen parameters, the voluntary-emissions game with international permit trading (policies A and B) yields lower global emissions than policy A alone. Moreover, the permit-importing country 2 has a marginal abatement cost, which is *below* its marginal damage cost. This property holds true in the more general case for any permit importer, see equation (10). It also offers some reasons why taxes (when included) will typically not vanish. When policies A, B, and C are combined, the emissions profile and therefore also efficiency are identical to those under policy A alone (illustrating Proposition 1). Moreover, the

[7] If combining equation (1) with Proposition 1 and equation (11), it also follows that a permit-exporting country subsidizes domestic emissions, while a permit importer employs a positive tax.

Table 1. *Outcomes for the example*

	Policy A			Policies A and B				Policies A, B, and C				
i	e_i	$\pi'_i(e_i)$	$W_i(\cdot)$	ω_i	e_i	$\pi'_i(e_i)$	$W_i(\cdot)$	ω_i	t_i	e_i	$\pi'_i(e_i)$	$W_i(\cdot)$
1	8	2	28	9	6	4	36	$9\frac{1}{3}$	$-2\frac{2}{3}$	8	2	$34\frac{2}{9}$
2	2	6	−44	0	3	4	−45	$\frac{2}{3}$	$1\frac{1}{3}$	2	6	$-50\frac{2}{9}$
Total (p)	10		−16	9	9	(4)	−9	10		10	$(4\frac{2}{3})$	−16

high-damage country 2 transfers money via the permit market to the low-damage country 1. Hence, the low-damage country wins and the high-damage country loses when policies B and C are combined with policy A (illustrating Proposition 2). Finally, and as noted in Footnote 7, the permit exporter subsidizes domestic emissions, while the importer taxes them.

IV. Bibliographic Remarks

The body of literature this paper is most closely related to (Copeland and Taylor, 1995; Helm, 2003; Holtsmark and Sommervoll, 2008; Carbone *et al.,* 2009; Cramton and Stoft, 2010a,b) has an international permit market explicitly at center stage, where the initial allocation of permits results from a non-cooperative game, and where no group of agents ever engages in maximizing their joint objectives. In contrast, each and every government always stands alone. The main contribution of our paper to this body of literature is to make taxes that influence the emissions part of the game.

When it comes to the tax instrument, this study is related to Hoel (1992a, 1993); Copeland and Taylor (1994, 2004), Santore *et al.* (2001), and Fankhauser *et al.* (2010), among others. In the papers by Hoel, it is emphasized that the introduction of a tax on carbon emissions, as part of an international agreement, could imply that signatories will find it interesting to adjust other domestic taxes, including those on fossil fuels; as such, this would undermine the effect of the agreement. Of the above-mentioned studies, Santore *et al.* (2001) and Fankhauser *et al.* (2010) combine the use of taxes and tradable permits, the initial allocations of which are exogenously given.

Our paper is also related to some literature on international trade agreements, in the sense that governments might use multiple domestic instruments that undermine the effects of international obligations (see, for example, Copeland, 1990; Bagwell and Steiger, 2001; Ederington, 2001).

Finally, this paper differs from the more standard, and much larger, body of literature dealing with international environmental agreements, where joint welfare maximization among the signatories is the starting point for the determination of national targets, possibly transferable. See Hoel

(1992b), Carraro and Siniscalco (1993), Barrett (1994), and Chander and Tulkens (1995) for early contributions, and see Chander (2003) for an illustration of how emissions trading might be used as a vehicle to facilitate side-payments for achieving efficiency. For a recent and good overview of the body of literature on climate change and game theory, see Wood (2010).

V. Concluding Remarks

Fundamental theorems on welfare economics provide good reasons for making rights to release greenhouse gases transferable. However, when the initial allocation is not determined by nature or any central agency, the arguments become more delicate. In particular, it complicates matters that the amount and distribution of permits must be approved by individual governments. Moreover, the demands of these bodies could depend on whether trade is permitted.

In this paper, we have identified an incentive that governments would have for using the tax instrument on domestic emissions, even for countries that participate in permit exchange. Our main finding is that if governments fully act on this incentive, it will affect their quota demands in such a way that international emissions trading will achieve nothing, besides redistributing income away from countries with high marginal climate costs.

While it is not surprising that non-cooperative behavior yields inefficient outcomes, our results complement and contrast the earlier body of literature. Even though we have demonstrated how emissions taxes and tradable pollution permits should *not* be used, this does not imply that they *cannot* be used for the purpose of achieving efficiency. Nevertheless, given the structure of incentives that are at work, our analysis aligns with the body of literature that points towards the challenges involved in achieving such objectives.

The conclusions from our analysis are sensitive to how the game was set up. Other specifications are clearly possible, including the following three.

1. We have assumed that the decisions of governments are unconstrained. It would be interesting to investigate, say, the implication of banning subsidies (i.e., imposing $t_i \geq 0$ for all $i \in I$). Even though we do not have results for this case, it is clear that such constraints will come into effect.
2. One can envisage other orders of moves. Suppose, for instance, a three-stage game where taxes are chosen second. While such a scenario seems perfectly reasonable, the analysis becomes analytically delicate, in particular if we insist on strategic behavior, subgame perfection, and not sacrificing the generality of π_i and v_i.

3. We also take for granted that firms in all countries have access to an international permit market. Thus, the only way a government can obtain a marginal abatement cost, which would differ from the international permit price, is to impose a domestic tax or subsidy. One could alternatively suppose that only governments are engaged in international trade, and that domestic emissions are regulated directly. A government that behaves strategically on the international permit market can then achieve a marginal abatement cost, which would be different from the international permit price (and without using the tax instrument). Such a scenario is widely studied for classical exchange economies (see, for example, Postlewaite, 1979; Gabszewicz, 2002, Section 4.4), and it is discussed for permit markets in Godal and Meland (2010, Section 6). However, in that body of literature, which is free of environmental externalities, endowments are exogenous. Here, they are part of the game, and, although it is straightforward to define such a game, its analysis becomes more complicated.

We do not think our exercise is sufficiently complete to warrant strong policy implications.[8] There are many and obvious reasons for this. Nevertheless, we emphasize that all the good properties of emissions trading programs applied to environmental problems, confined to a single jurisdiction, do not immediately carry over to an international setting, in either theory or practice so far. The generous targets allowed by the Kyoto Protocol are an obvious reminder of this. Moreover, even if permits were to be traded in large quantities, our analysis suggests that it does not automatically follow that the apparent efficiency gains will be an improvement over the policies that would otherwise have arisen.

Appendix A: Proof of Lemma 1

Under the assumed conditions, there exists a continuously differentiable demand function $f_i := (\pi_i')^{-1}$ for each firm $i \in I$, such that

$$e_i = f_i(p(\boldsymbol{\omega}, \mathbf{t}) + t_i), \tag{A1}$$

where, using the inverse function theorem, $f_i' = 1/\pi_i''$. From equation (A1), it then follows that

$$\frac{\partial e_i}{\partial \omega_i} = \frac{1}{\pi_i''(e_i)}\frac{\partial p}{\partial \omega_i}, \quad \frac{\partial e_i}{\partial t_i} = \frac{1}{\pi_i''(e_i)}\left(\frac{\partial p}{\partial t_i} + 1\right), \quad \text{and} \quad \frac{\partial e_j}{\partial t_i} = \frac{1}{\pi_j''(e_j)}\frac{\partial p}{\partial t_i}, \tag{A2}$$

[8] Cramton and Stoft (2010a,b) offer more material on this matter. They also set up an international price commitment game, showing, among other results, that it has a preferable outcome.

where the last statement applies when $j \neq i$. Market clearing requires

$$\sum_{j \in I} f_j(p(\boldsymbol{\omega}, \mathbf{t}) + t_j) = \sum_{j \in I} \omega_j. \tag{A3}$$

Differentiating the last equality throughout with respect to ω_i and t_i yields

$$\frac{\partial p}{\partial \omega_i} = \frac{1}{\sum_{j \in I}[1/\pi_j''(e_j)]} \quad \text{and} \quad \frac{\partial p}{\partial t_i} = -\frac{[1/\pi_i''(e_i)]}{\sum_{j \in I}[1/\pi_j''(e_j)]}. \tag{A4}$$

This takes care of the first statements in equations (4) and (5). We apply equation (A4) in equation (A2) together with definition (3) to obtain the remaining claims in equations (4) and (5). The results in equation (6) follow directly from equation (2) or alternatively from equations (4) and (5). ■

Appendix B: Proof of Proposition 1

Combining the first-order optimality conditions (7) and (8) with definition (3) and the results from Lemma 1, it follows that the said first-order optimality conditions reduce to

$$(\pi_i' - p)\frac{s_i}{S} + p + \frac{1}{S}(\omega_i - e_i) - v_i' = 0 \tag{B1}$$

and

$$(\pi_i' - p)\left(1 - \frac{s_i}{S}\right) - \frac{1}{S}(\omega_i - e_i) = 0, \tag{B2}$$

respectively. We add the left-hand sides of equations (B1) and (B2) to obtain $\pi_i' - v_i' = 0$, as in equation (9). The assumption on the existence of a unique equilibrium completes the proof. ■

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Essay 4
Harvesting in boreal forests and the biofuel carbon debt

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Harvesting in boreal forests and the biofuel carbon debt

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Abstract Owing to the extensive critique of food-crop-based biofuels, attention has turned toward second-generation wood-based biofuels. A question is therefore whether timber taken from the vast boreal forests on an increasing scale should serve as a source of wood-based biofuels and whether this will be effective climate policy. In a typical boreal forest, it takes 70–120 years before a stand of trees is mature. When this time lag and the dynamics of boreal forests more generally are taken into account, it follows that a high level of harvest means that the carbon stock in the forest stabilizes at a lower level. Therefore, wood harvesting is not a carbon-neutral activity. Through model simulations, it is estimated that an increased harvest of a boreal forest will create a biofuel carbon debt that takes 190–340 years to repay. The length of the payback time is sensitive to the type of fossil fuels that wood energy replaces

1 Introduction

Carbon neutrality of bioenergy combustion is incorporated into most countries' climate policies. No country imposes taxes on CO_2 emissions from the combustion of bioenergy. Moreover, the European Union emissions trading scheme incorporates the assumption that bioenergy is a carbon-neutral fuel; firms included in this market are not committed to acquiring and surrendering allowances for emissions from the combustion of bioenergy.

The reasoning behind the carbon neutrality assumption is that the harvest of one crop is replaced by the growth of a new crop, which reabsorbs the quantity of carbon that was released by burning the first crop. This is a reasonable argument in the case of food-crop-based biofuels, as new crops replace those that are harvested, usually within 1 year. However, the carbon neutrality of food-crop-based biofuels has recently

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been questioned. Fargione et al. (2008) found that converting native habitats to cropland releases CO_2 from both existing vegetation and carbon stored in soils. Fargione et al. (2008) therefore concluded that production of food-crop-based biofuels may create a biofuel carbon debt by releasing CO_2 at a level that is many times the level of annual greenhouse gas reductions that these biofuels would provide by displacing fossil fuels.

Searchinger et al. (2008) analyzed the global effects of using grain or existing cropland for biofuel production. They argued that most previous analyses failed to take account of the carbon emissions that occur as farmers worldwide respond to higher crop prices and convert forest and grassland to new cropland to replace the grain or cropland diverted to biofuels; see also Gibbs et al. (2010); Gurgel et al. (2007); Lapola et al. (2010), and Melillo et al. (2009), among others.

More generally, Wise et al. (2009) and Searchinger et al. (2009) underlined that the current practice of accounting for CO_2 emissions from combustion of bioenergy as zero means there are strong incentives to clear land, thus releasing large amounts of greenhouse gases.

The criticism of food-crop-based biofuels has not been directed toward wood-based biofuels to the same degree, at least not wood fuels from boreal forests. Even within the research community it has been common to consider timber from boreal forests as a carbon-neutral energy source; see for example Bright and Strømman (2009); Petersen and Solberg (2005); Raymer (2006); Sjølie et al. (2010); Sjølie and Solberg (2009), and Zhang et al. (2010). Especially, the possibility of producing liquid biofuels from cellulosic biomass (second-generation biofuels) is considered a promising alternative to using food crops (Hill et al. 2006).

This article therefore analyzes the effects of wood fuels from boreal forests with regard to the release of CO_2 into the atmosphere. It would be reasonable to argue that wood fuels are carbon neutral if new trees grew so fast that they replaced those that are felled a year later or at least after only a few years. However, this is not the case in a boreal forest. Even after 10 or 20 years, new trees are still only saplings. In typical boreal-forested areas, it usually takes 70–120 years before a stand of trees is mature (Storaunet and Rolstad 2002). As will be shown in Section 3, this long growth period implies that a higher level of harvest entails a lower stock of carbon stored in the forest. Hence, the assumption that wood fuels from boreal forests are climate neutral should be replaced with realistic assumptions about the dynamic consequences of harvest in a boreal forest.

In this article, I use model simulations to study how increasing the harvest from the Norwegian forest by 30%, starting in 2010 will influence the net release of CO_2 into the atmosphere. With regard to the use of the wood harvested, two cases are considered. In the first case, I assume that the wood is used as the raw material for manufacturing pellets. The pellets then replace coal in power plants. This is a relevant example because power producers in Europe are committed to acquiring and surrendering allowances for emissions resulting from fossil-fuel combustion only, not for emissions resulting from the combustion of bioenergy. In the case of Norway the example has special relevance, as the world's second-largest wood-pellet production plant (BioWood Norway) has recently been established on the west coast of Norway, and it will manufacture pellets on a large scale for this purpose.

In the second example, I look at the use of wood to produce second-generation liquid biofuels. This example is relevant as NCPA (2010) presented ambitious scenarios for the production of second-generation liquid biofuels based on wood.

The simulations show that increasing the harvest in a boreal forest will cause a significant initial release of CO_2. Along the lines of Fargione et al. (2008), I label this release of CO_2 from the forest as a carbon debt. Over time, the carbon debt could be repaid through regrowth in the harvested area and through replacement of fossil fuels as an energy source. In this study, the payback time is found to be within the interval of 190–340 years, depending on the type of fossil fuel that the wood fuel replaces.

The model simulations in this article are based on the properties of a Norwegian forest. However, the conclusions are relevant to boreal forests more generally. Additionally, it should be kept in mind that boreal forests store almost twice as much carbon as tropical forests (Kasischke 2000, p. 20).

A closely related study is that conducted by McKechnie et al. (2011), although they studied a temperate forest in Ontario with faster regrowth. Their model simulations have a timeframe of 100 years, while I present simulations 400 years into the future. In the case in which pellets replace coal in power plants, McKechnie et al. (2011) deduced a payback time shorter than that determined in this article. However, this is as expected after taking the more rapid growth in temperate forests into account. McKechnie et al. (2011) did not specify the payback time when wood fuels replace liquid fossil fuels, as this was beyond their simulation timeframe.

Another closely related report is “Biomass Sustainability and Carbon Policy Study” published by the Manomet Center for Conservation Sciences (2010). They calculated a payback time shorter than that determined in this study. However, the Manomet report considered single-harvest events only. As discussed in Section 3.1 and in the supplemental online material, this makes a large difference.

It should also be mentioned that this article analyzes the consequences of taking bioenergy from boreal forests when the supply of bioenergy is generated through increased harvest. Using by-products from the forest industry as bioenergy is a different and less controversial matter, and is not discussed in this article. One should, however, be aware that increased demand for by-products from the forest industry could increase the harvest through indirect market effects.

The next section presents the model and crucial assumptions made. Section 3 discusses a number of model simulations. First, Section 3.1 considers the relationship between the harvested volume and the forest’s carbon stock in long-term steady states. Second, Section 3.2 describes the consequences in both the short and long terms of increasing the annual harvested volume. Third, Section 3.3 studies the net effects on CO_2 emissions when the increased harvest considered in Section 3.2 is used as bioenergy and replaces fossil fuels. The findings are discussed in Section 4. The supplemental online material provides firstly a detailed model description with all parameter values. Furthermore, the online material (1) clarifies the importance of considering not only a single-harvest event in the case where a permanently higher harvest level is to be analyzed, and (2) presents two scenarios where greater harvest is achieved through expansion of the harvested area, rather than adjusting the rotation length as considered in Sections 3.2 and 3.3.

2 Model and methods

The model contains a fixed set of 75 000 parcels, each parcel covering an area of 1 km^2, and all having identical dynamic properties with regard to accumulation of dead and living biomass. However, the time since the last clear-cutting in the parcel (i.e., the parcels’ stand age) varies. The Norwegian forest has a high proportion of young stands; see Larsson and Hylen (2007). On the basis of their work an age structure in the starting year of the simulations is assumed such that the stand age for 37% of parcels is less than

30 years, while that for 21% is more than 80 years. Hence, the stand age for 42% of parcels is between 30 and 80 years. For further details, see the supplemental online material.

Essential for the dynamics of the model is that immediately after clear-cutting has taken place in a parcel, the parcel's volume of living biomass drops to zero, and thereafter, the growth path described in Fig. 1 begins again. The volume of living biomass in a single parcel depends solely on the parcel's stand age. The parcel's productivity is fairly normal for a boreal forest and is close to the growth path of productivity class 14 defined by Braastad (1975).

An important part of the model is the module taking care of carbon stored in deadwood. The trunks are assumed to constitute 48% of the living biomass. Hence, after clear-cutting a significant amount of harvest residues is left on the parcel (see Fig. 1). Different "cohorts" of natural deadwood and harvest residues are treated separately. With regard to the speed of decomposition of deadwood, there is uncertainty. On the basis of the discussion presented by Liski et al. (2005), I assumed that 75% of harvest residues and 70% of natural deadwood decomposed in 50 years. After 100 years, both types of deadwood are assumed to have decomposed completely. Owing to the uncertainty of these points, however, the supplemental online material presents a number of sensitivity simulations with regard to these assumptions.

The accumulation of natural dead wood in each parcel of forest after felling and replanting is also shown in Fig. 1. Natural losses are low until the trees are 80–90 years old, increase sharply until the trees are 150 years old, and then gradually stabilize. Note that the periodization (time unit) in the model is 5 years.

Changes in the stock of biomass in old forests are uncertain (Carey et al. 2001; Pregitzer and Euskirchen 2004; Seely et al. 2002). It is here assumed that there is a constant volume biomass of older stands; see Fig. 1. As more recent data suggest that old growth forests are significant carbon sinks (see Luyssaert et al. 2008), this might be considered conservative. Assuming that older stands continue to accumulate carbon would imply a longer payback

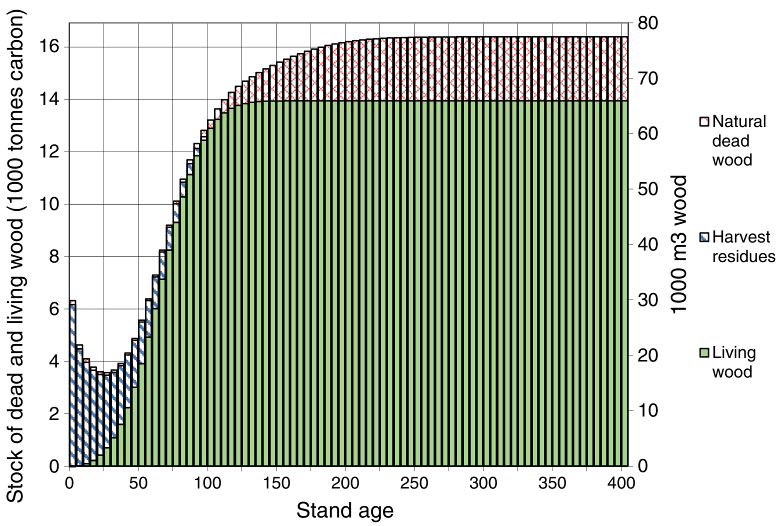

Fig. 1 A single parcel. The development of the volumes of living wood, harvest residues and natural deadwood after clear-cutting and replanting in the standard parcel. Stand age at time of last felling was 95 years

time of the carbon debt than found in this article. However, owing to the uncertainty of this point, and claims that the probability of carbon loss due to different types of disturbances is greater in older forests, Holtsmark (2010) assumed, as a very conservative estimate, that the stock of wood and thus the carbon stored in the biomass decline substantially as a parcel ages. Holtsmark (2010) therefore deduced a payback time shorter than that determined in this article.

An important point is the role of soil as a carbon sink. In a boreal forest, in contrast to a tropical rain forest, a large share of the carbon is stored in the soil. According to Kjønaas et al. (2000), more than 80% of carbon in Norwegian forests is stored in the soil. An important question is therefore whether harvest is likely to trigger the release of carbon from soil. As underlined by Fontaine et al. (2007); Friedland and Gillingham (2010), and Nilsen et al. (2008), the accumulation and possible release of carbon from the soil are complicated processes that are not easily modeled. I have therefore chosen to ignore the possibility that harvesting may reduce the capacity of the soil as a carbon sink, and have considered only how harvesting influences the stock of carbon stored in dead and living biomass, although Nakane and Lee (1995) and Nilsen et al. (2008) suggest that clear-cutting might trigger the release of carbon from soil, especially if tops and branches are harvested in addition to trunks. This last point is further underlined by Holmgren et al. (2007); Kujanpää et al. (2010); Kirkinen et al. (2008); Palosuo et al. (2001); Repo et al. (2011), and Schlamadinger et al. (1995). Hence, the estimated payback time of the carbon debt would probably have been longer if I had relied on less conservative assumptions at this point.

The carbon content of a cubic meter of biomass depends on the wood's density. I assume throughout a density of 423 kg/m^3, and that half of the mass is carbon. This gives 0.211 tonnes of carbon per m^3, or 0.774 tonnes CO_2 per m^3 wood used as fuel. For further details, see the supplemental online material.

3 Results

3.1 Relationship between the length of the rotation cycle and the carbon stock in different steady states

Figure 2 provides relevant information for a discussion on carbon neutrality. It shows the volume of timber felled annually (curve) and the entire forest's stock of carbon in dead and living wood (columns) for rotation cycles of different lengths (horizontal axis).

It should be noted that Fig. 2 considers the entire forest area of 75000 km^2 and shows the forest in different *steady states*, in the sense that the length of the rotation cycle is constant and has been constant for so long that both the harvest and standing volume are also constant over time.

Figure 2 confirms that the maximum harvest (*volume felled*) is obtained with a rotation cycle of 90 years. The *carbon stock* of dead and living biomass, on the other hand, monotonously increases as the rotation period is extended.

The stock of carbon is almost twice as large with a 250-year rotation cycle as with a 90-year rotation cycle. This may seem difficult to reconcile with Fig. 1, which shows that the stock of carbon in a single parcel increases by less than 25% as the stand age increases from 90 to 250 years. The explanation is that as the length of the rotation cycle increases, there are fewer and fewer parcels that have recently been clear-cut. In other words, if the rotation cycle is long, a large share of the parcels will at any point in time carry a large stock of wood. If the

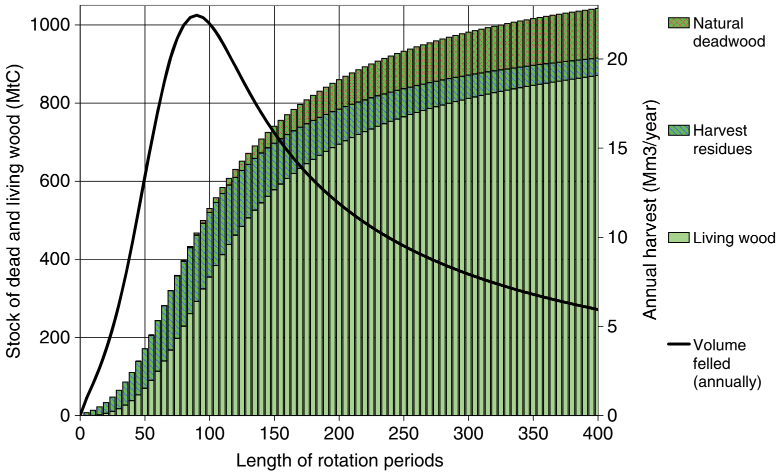

Fig. 2 The entire forest. Annual volume of timber felled (black curve) and quantity of carbon stored in dead and living wood (columns) in different steady states for rotation cycles of different lengths

rotation cycle is short, on the other hand, a large proportion of the forest will at any point in time be relatively recently felled, and its stock of wood will be correspondingly small.

Figure 2 indicates that it is misleading to claim that wood provides carbon-neutral bioenergy, even in the long term. It shows that if the harvest is permanently large, which requires short rotation cycles, the carbon pool of the forest will be permanently small. In contrast, if the annual harvest is small, with correspondingly long rotation cycles, the carbon pool will be permanently large. With a 90-year rotation cycle, for example, an area of 833 km^2 can be felled each year, giving an annual harvest of 22.5 million cubic meters (Mm^3) of timber and 467 million tonnes of carbon (MtC) stored in dead and living wood. With a 250-year rotation cycle, 300 km^2 can be felled annually and the annual harvest is only 9.5 Mm^3; the carbon stored in dead and living wood, on the other hand, rises to 933 MtC (see Table 1).

In other words, increasing the harvest to a higher level on a permanent basis does not merely result in a *temporary* drop in the forest's carbon stock that will in the long term be entirely counterbalanced by CO_2 uptake by the forest. On the contrary, a *permanent* increase in the harvest results in a *permanently* lower forest carbon stock. Hence, increasing the harvest level is not a carbon-neutral change, either in the short term or in the long term.

This also shows that the question of carbon neutrality cannot be resolved by studying the effect of a single harvest in a single year with subsequent planting. Such a single-event perspective is an oversimplification that does not incorporate the important long-term

Table 1 Example of two different steady states

Length of the rotation cycle (years)	Annual harvest (Mm^3)	Area harvested (km^2/year)	Carbon stored in dead and living biomass (MtC)
90	22.5	833	467
250	9.5	300	933

dynamic effects on the forest's carbon stock (see the supplemental online material for further discussion).

At this point, the report on biomass sustainability presented by the Manomet Center for Conservation Sciences (2010) should be mentioned. This report considers only a single-harvest event rather than conducting "…a more complicated series of repeated harvest entries." (ibid. p. 85). The Manomet report is important along different lines, as it contains new information and provides an interesting discussion on the carbon neutrality of wood energy. However, the report's relatively optimistic conclusions with regard to the time lag between harvest, the released volume of carbon dioxide, and the payback time of the carbon debt reflect the report's single-harvest approach and therefore do not take into account important features of the long-term effect of a higher level of harvest on the forest's carbon stock. As shown in the supplemental online material, the payback time more than doubles if a series of subsequent harvest events are considered instead of a single-harvest event.

3.2 Short-term and long-term effects of increasing the harvest

The previous section considered the carbon stock of a forest in a steady state in the sense that the rotation cycles were constant over time, giving the forest an even age structure. This section describes the short-term and long-term effects of increasing the harvest in a forest with an uneven age structure similar to the age structure found for a Norwegian forest.

In the reference scenario, the annual harvest is 10 Mm^3 and no residues are harvested. This is compared with a scenario where the annual harvest increases by 3 Mm^3 to 13 Mm^3, with 2010 as the first year of increased harvest. In addition, this scenario assumes that 0.6 Mm^3 of residues is harvested annually.

The chosen numerical example has relevance, as the annual harvest from Norwegian forests has varied around 10 Mm^3 for several decades (NCPA 2010). However, the Norwegian government wants to increase the harvest to increase the supply of bioenergy, and an increase in the annual harvest to 13 Mm^3 is frequently discussed; see NCPA (2010).

What effect does a higher harvest level have?

Given the assumed age structure, with a large share of the parcels having a low stand age, and because the annual harvest is limited to 10 Mm^3 in the reference scenario, the forest's carbon stock increases until the end of the 22nd century (see Fig. 3). Moreover, even if the harvest is increased to 13 Mm^3, the forest's carbon stock increases over this period, although at a lower rate. Recall here that the maximum harvest that could be sustained in a steady state is 22.5 Mm^3/year; see Fig. 2.

It is important to note that Fig. 2 shows different steady-state situations for rotation cycles of different lengths, whereas Fig. 3 shows the transition from the current state of the forest to towards a new steady state.

For further clarification, consider the reference (small-harvest) scenario as illustrated by the upper curve in Fig. 3. The figure shows that by 2100, the stock of carbon has more than doubled from the 2005 level to 857 MtC (see also Table 2). However, Figure 3 also shows that in the larger-harvest scenario, the carbon stock is only 775 MtC in 2100. In other words, the increase in the harvest has resulted in a carbon stock that is 82 MtC lower in 2100 than it would have been with the lower harvest level. More generally, the vertical distance between the upper and lower curves in Fig. 3 shows the net reduction in the forest's carbon stock as a result of the greater harvest; see also the red curve in Fig. 4.

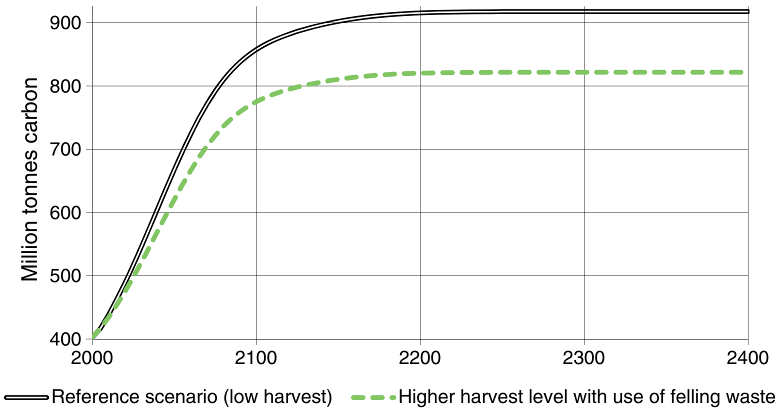

Fig. 3 Carbon stored in wood in the two scenarios considered in Sections 3.2 and 3.3

3.3 Reducing the use of fossil energy by increasing the use of wood energy

The previous section considered how felling affects the stock of carbon stored in the forest's dead and living wood. The argument for felling more timber is precisely that using wood as a source of bioenergy can reduce the use of fossil energy and thus cut CO_2 emissions. In this section, I consider the extent to which increasing the timber harvest for bioenergy production can replace the use of fossil energy. Taking account of both the replacement effect on fossil fuel combustion and the effects on the forest's carbon stock, it is possible to calculate the net CO_2 effects of increased logging.

The quantity of fossil energy that wood fuels can replace varies widely depending on precisely which technologies are involved. Here I discuss two examples that show how two different types of wood fuels will affect net CO_2 emissions. In the first case, I have assumed that the wood is used as the raw material for manufacturing pellets. The pellets then replace coal in power plants. In the second example, I look at the use of wood to produce second-generation liquid biofuels.

The exact volumes of CO_2 emissions that can be eliminated using wood energy are of great importance. On the basis of the works of Sjølie and Solberg (2009) and Weisser (2007), I have assumed that using 1 m^3 of wood, processed to pellets, instead of coal in a power plant can eliminate 0.5 tonnes of fossil-generated CO_2 emissions. The method used to calculate this figure is described in further detail in the supplemental online material.

Table 2 Carbon stock, emission reductions, and remaining carbon debt in the scenarios considered in Section 3.2. All figures are in millions of tonnes of carbon

	2005	2100	2200	2300
Carbon stored in biomass in reference (small-harvest) scenario	417	857	915	918
Carbon stored in biomass in large-harvest scenario	417	775	820	822
Drop in carbon stock due to increased harvest	–	82	95	96
Accumulated reductions in fossil carbon emissions—wood fuels replace coal	–	46	95	144
Remaining carbon debt—wood fuels replace coal	–	36	0	−48
Accumulated reductions in fossil carbon emissions—wood fuels replace oil	–	26	54	81
Remaining carbon debt—wood fuels replace oil	–	56	42	15

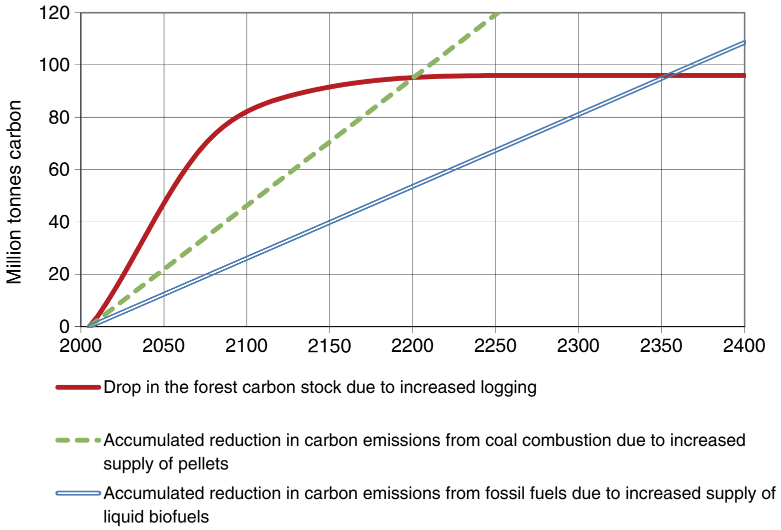

Fig. 4 The two straight lines show the accumulated reductions in CO_2 emissions from combustion of fossil energy achieved by increasing the supply of bioenergy through a higher harvest level. The red curve in Fig. 4 shows the difference in the carbon stock between the small- and large-harvest scenarios

To calculate the volume of fossil emissions that can be eliminated using second-generation biofuels, I followed NCPA (2011, p. 32). This report concludes that using 1 m^3 of wood processed to second-generation liquid biofuel can eliminate 0.28 tonnes of CO_2 emissions generated through the combustion of fossil fuels.

We are now ready to calculate the net effect of the increased harvest on accumulated CO_2 emissions. Recall that the overall increase in the annual harvest is 3.6 Mm^3 when a share of the residues is also harvested. From Fig. 4 it is possible to gain a visual impression of the results by comparing the lines with the curve. The red curve in Fig. 4, the elevation of which is equal to the vertical distance between the curves in Fig. 3, shows the difference in the carbon stock of the forest between the large- and small-harvest scenarios. The lines show the *accumulated* fossil CO_2 emissions that can be eliminated by increasing the volume of timber harvested and using this harvest to replace fossil fuels in the two ways discussed. The remaining carbon debts in the two cases considered are equal to the vertical distance between the red curve and the two lines in Fig. 4. As long as the curve is above the considered line, the remaining carbon debt is positive. When the line is above the curve, the carbon debt has been fully repaid and a carbon dividend is collected, using the term introduced by Manomet Center for Conservation Sciences (2010).

Firstly, consider the case where the wood is processed to pellets and replaces coal in a power plant. In that case, each cubic meter of wood eliminates 0.5 tonnes of fossil-generated CO_2 emissions. This means that 1.8 $MtCO_2$ or 0.5 MtC of fossil emissions are eliminated each year. Hence, by 2100, fossil CO_2 emissions corresponding to 46 MtC have been eliminated (see Table 2 and the broken line in Fig. 4).

As mentioned, the increased harvest means that the carbon stock of the forest by 2100 is 82 MtC less than it would have been if the annual harvest had been maintained at 10 Mm^3. Subtracting 46 MtC (the accumulated drop in fossil carbon emissions), it follows that in the pellets case, the remaining carbon debt in 2100 is 36 MtC. In other words, although increasing the harvest eliminates fossil CO_2 emissions from coal combustion corresponding to 46 MtC, the net accumulated release of carbon to the atmosphere will be 36 MtC higher in the period 2010–2100 in the large-harvest scenario than in the reference (small-harvest) scenario.

The development of the remaining carbon debt is shown in Fig. 5. Note that the elevations of the curves in Fig. 5 are equal to the vertical distances between the red curve and the two lines in Fig. 4. Figure 5 shows that in the pellet case, the remaining carbon debt is declining in 2100 and becomes negative around 2200, that is, 190 years after the increase in the harvest. Hence, the analysis suggests that increasing the harvest and the use of wood fuels to replace coal in power plants could, for a long period of time, result in significantly greater CO_2 emissions than the combustion of the coal that the increased harvest replaces.

Secondly, consider the effect of using the extra harvest of wood as raw material in the production of second-generation liquid biofuels. In that case, each cubic meter of wood eliminates 0.28 tonnes of fossil-generated CO_2 emissions. This means that 1.01 $MtCO_2$ or 0.27 MtC of fossil emissions are eliminated each year. Hence, by 2100, fossil CO_2 emissions corresponding to 26 MtC have been eliminated; see the level of the lower line in 2100 in Fig. 4, which shows the *accumulated* reduction in fossil carbon emissions in this case.

The lower line in Fig. 4 is below the red curve throughout the 21st, 22nd, and 23rd centuries, and crosses the red curve in 2350. Thus, the calculations indicate that using second-generation liquid biofuels produced from boreal timber rather than continuing to use fossil diesel may actually *increase* the net accumulated release of CO_2 for 340 years, i.e. generate a carbon debt that will be repaid only after more than three centuries. This is in contrast to the results obtained by assuming that wood is a climate-neutral fuel, where the effect on the forest's carbon stock is completely ignored and a carbon dividend is thus assumed to be generated from day one and to be equal to the elevation of the lines in Fig. 4.

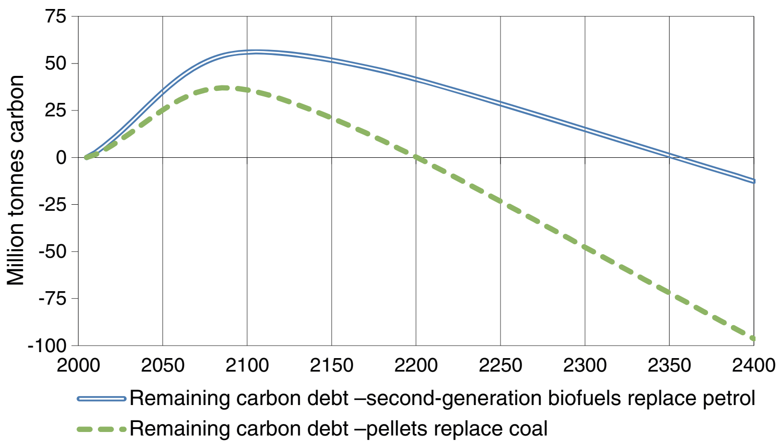

Fig. 5 Development of the remaining carbon debt due to increased harvest when the increased harvest is used to replace fossil fuels

4 Discussion and conclusion

Bioenergy is usually considered carbon neutral and an important part of a strategy for reducing CO_2 emissions; see for example IPCC (2000). The generation of biomass in boreal forests is significant and could potentially serve as an important source for an increased supply of bioenergy.

The traditional assumption that wood fuels are carbon neutral would have been appropriate if trees harvested were replaced by new trees within a short period of time. However, the typical life cycle of a spruce tree in boreal forests includes a growth phase that lasts about 100 years and then a phase in which the mass remains relatively stable for a further 100 years. The tree then dies, but remains standing for about 30 years before falling to the ground and gradually decaying over the course of the following 100 years (Storaunet and Rolstad 2002).

From that point of view, it appears obvious that harvest from boreal forests is not a climate-neutral activity. However, as should be made clear from the previous sections, forest dynamics cannot be understood by studying individual trees or a single harvest and subsequent regeneration of the felled trees. I have therefore described and simulated a dynamic model of the Norwegian forest.

In the simulations presented in this article, the harvest is increased by 30%, while the forest increment is still positive over the whole of the 21st century. Nevertheless, the increase in the harvest means that the carbon stock in the stylized forest stabilizes at a different level, as would be expected. Hence, even if the forest increment is positive, wood harvesting and combustion are not carbon-neutral activities.

The article also presents calculations illustrating the net effect on the CO_2 release of increased logging when the biomass made available replaces fossil fuels as energy sources. Two examples are described: processing wood to pellets for use in coal-fired power plants, and processing wood to liquid biofuels, which are used to replace fossil oil.

The article's first main finding is that increasing the use of wood from a boreal forest to replace coal in power plants will create a carbon debt that will only be repaid after approximately 190 years. Secondly, if the wood is used to produce second-generation liquid biofuels and replaces fossil diesel, the payback time of the carbon debt is estimated to be 340 years.

In addition, it is important to remember that the analyses presented here do not take into account the effect of providing subsidies for various alternative forms of energy as a means of reducing the use of fossil energy. Such subsidies tend to increase overall energy use; see for example Hutchinson et al. (2010). If this is taken into account, the emission-increasing effect of using wood as energy will become even more pronounced. A complete analysis should also include such effects.

An uncertain aspect of the parameterization of the model is the determination of changes in the volume of deadwood over time. Sensitivity calculations were therefore carried out to test the effect of varying the rate of decay for deadwood. These simulations show that the parameterization is not a critical factor (see the supplemental online material).

Nevertheless, it should be stressed that the purpose of this article is not to provide definitive answers but to draw attention to the importance of taking both short- and long-term dynamic effects of increasing the timber harvest more fully into account when evaluating the effect on emissions of increasing the use of energy from wood combustion. The analysis carried out here could be improved along several dimensions, not least considering more heterogeneous forests with areas of different productivity while taking full account of how harvest in boreal forests influences the amount of carbon stored in the soil. Another topic for future research should be the capacity of old growth forests as carbon stores when the likeliness of disturbance is taken into account, and how the frequency of disturbance might change in a warmer climate. And finally, it should be noted that this paper calculate estimates of the effects on accumulated net release of CO_2 into the atmosphere along different time horizons only. To provide a complete picture of the climatic effects of this would require a model of the relationship between net release of CO_2, its persistence in the atmosphere and the corresponding effects on radiative forcing, as well as possible albedo effects of clear-cutting in boreal forests.

It should also be underlined that the analysis presented here does not make arguments against the use of bioenergy from boreal forests in general. If bioenergy is obtained through increased use of residues from different forest-related industries, the CO_2 effects are probably favorable.

Nevertheless, the commonly applied assumption that wood fuels are climate neutral is not tenable. If this assumption is reevaluated, it may also be necessary to reevaluate the current taxes and subsidies that apply to bioenergy and forestry. It is not at all clear whether current policy takes sufficient account of the potential of forests as carbon sinks or of the fact that burning wood results in CO_2 emissions. As highlighted by Searchinger et al. (2009), for example, putting a high price on CO_2 emissions from fossil energy emissions while considering bioenergy to be carbon neutral would create strong incentives to clear land.

The claim that using wood fuels is carbon neutral is based on the approximation that logging has a negligible effect on the forest's carbon stock. This would be a reasonable approximation if there were a negligible time lag between felling and full regrowth. The carbon-neutrality claim ignores the significance of this time lag, and the dynamics that follow, not least that there will be a permanent reduction in the stock of both dead and living biomass in the forest if the harvest is permanently increased. Thus, making the common assumption that using wood as bioenergy is carbon neutral also means that it is assumed that all the effects on the forest's carbon stock are so small that they can be ignored.

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APPENDIX TO THE FOURTH ESSAY*

HARVESTING IN BOREAL FORESTS AND THE BIOFUEL CARBON DEBT

This supplemental online material provides initially a detailed model description with all the parameter values and a number of sensitivity simulations with regard to the decomposition rate of deadwood. Furthermore, it clarifies the importance of considering not only a single harvest event in the case where a permanently higher harvest level is to be analyzed, and presents two scenarios where a greater harvest can be achieved through expansion of the harvested area, rather than adjusting the rotation length, as considered in sections 3.2 and 3.3 in the article.

1 THE MODEL

1.1 THE STRUCTURE OF THE MODEL

First, this section explains the structure of the model. Second, the chosen functional forms and parameter values are presented.

Borrowing a term from economics, the model could be considered as an "overlapping-generations" model of parcels with different stand ages. However, while the population size of an overlapping-generations model usually varies over time, the modeled forest contains a *fixed* set of parcels, I, with each parcel covering an area of 1 km^2. The number of parcels is labeled n. Essential for the dynamics of the model is that immediately after clear-cutting has taken place in a parcel, the parcel's volume of living biomass is zero and the growth path described in section 1.2 below restarts.

Let B_t and B_{it} be the volumes of living biomass in the entire forest and in parcel number i at time t, respectively. It follows that

$$B_t = \sum_{i \in I} B_{it}. \tag{1}$$

The volume of biomass in a single parcel depends solely on the time since last clear-cutting in that parcel (i.e., the parcel's stand age $\tau_i(t)$):

$$B_{it} = B(\tau_i(t)). \tag{2}$$

The function $B(\tau_i(t))$ is further described in section 1.2.

* This appendix to the fourth essay is identical to the supporting online material to the orginal article published in Climatic Change.

Define F_t as the set of parcels where clear-cutting takes place at time t. Define w as the share of the biomass harvested. The harvested volume H_t at time t is then given by

$$H_t = w\sum_{i\in F} B(\tau_i(t)). \tag{3}$$

The trunks are assumed to constitute s = 48 percent of the biomass of any parcel at any time. Hence, to the extent that $w > s = 0.48$, residues are also harvested.

It follows that the volume of harvest residues left in the forest at time t is

$$\Delta_{Ht} = \frac{1-w}{w}H_t. \tag{4}$$

Let d_τ be the share of living trees in a parcel with stand age τ that does not survive until the next period. The amount of natural deadwood that parcel i generates in period t is

$$\Delta_{Nit} = d_{\tau_i(t)}B(\tau_i(t)),\ i = 1,\ldots,n. \tag{5}$$

It follows that the total volume of natural deadwood generated in period t is

$$\Delta_{Nt} = \sum_{i\in I}\Delta_{Nit}. \tag{6}$$

Let $\alpha_N(\tau)$ and $\alpha_H(\tau)$ be the shares of deadwood and harvest residues, respectively, that have not decomposed after τ years. Assume that deadwood decomposes completely over a period of T years. Hence, while $\alpha_N(0)= \alpha_H(0)= 1$, we have that $\alpha_N(N)= \alpha_H(N)= 0$. It follows that the total accumulated volume of natural deadwood and harvest residues in the whole forest in period t is

$$D_{jt} = \sum_{\tau=0}^{T}\alpha_j(\tau)\Delta_{jt-\tau},\ j = N,H. \tag{7}$$

1.2 Functional forms and parameter values

Functional forms and parameter values are chosen to simulate as realistically as possible the different dynamic properties of the Norwegian forest. To have a path of the stock of living biomass corresponding to a Norwegian spruce forest of medium productivity (cf. Braastad (1975)), a set of functions are added as follows

$$B_{it} = \frac{1}{s}\sum_{\tau=0}^{\tau_i(t)}\left(\sum_{j=1}^{2} g_j e^{x_j(\tau)}\right),\ i = 1,\ldots,n, \tag{8}$$

where g_1 and g_2 are parameters. The functions $x_j(\tau)$ are defined as

$$x_j(\tau) = -\frac{\left(\frac{\tau}{5}-m_j\right)^2}{k_j},\ j = 1,2, \tag{9}$$

where m_j and k_j are parameters.

The share of living trees d_{it} in parcel i with stand age τ_i(t) that does not survive period t is

$$d_{it} = \sigma\frac{Ke^{r\tau_i(t)}}{K-1+e^{r\tau_i(t)}},\ i = 1,\ldots, n, \tag{10}$$

where K, r, and σ are parameters. The following expressions are applied to the rate of decomposition of deadwood.

$$\alpha_j(\tau) = \begin{cases} 1-\left(\dfrac{\tau}{T}\right)^{\delta_j} & if\ \tau < T, j = N, F, \\ 0, & if\ \tau > T. \end{cases} \tag{11}$$

The values of all parameters are given in Table S1.

Table S1 Parameter values

Parameter	Value	Parameter	Value	Parameter	Value
g_1	2550	k_1	50	s	0.48
g_2	−1442	k_2	20	δ_N	0.576
m_1	13.3	K	350	δ_F	0.431
m_2	−7	r	0.053	n	75000
σ	6.25×10^{-5}	T	100		

The age structure of the wood in the starting year (2010; before felling) is based on the work of Larsson and Hylen (2005) and given in Table S2. Given this age structure, the chosen functional forms and the parameter values, it follows that in the starting year, the total volume of living wood is 1583 Mm^3, containing 334 MtC. With the assumed initial stocks of harvest residues (75 MtC) and natural deadwood (8 MtC), it follows that the forest's carbon stock (not including soil carbon) is 417 MtC in the starting year.

Table S2 Age structure of the forest in the starting year

Stand age (years)	Share of parcels (percent)	Stand age (years)	Share of parcels (percent)	Stand age (years)	Share of parcels (percent)
0–5	5.3	50	5.2	95	2.6
10	5.5	55	4.9	100	2.3
15	5.6	60	4.6	105	2.1
20	5.7	65	4.4	110	1.9
25	5.8	70	4.1	115	1.7
30	5.7	75	3.8	120	1.5
35	5.7	80	3.5	125	1.3
40	5.5	85	3.2		
45	5.4	90	2.9		

1.3 Carbon and energy content of wood and substitution effects

The theoretical energy output of wood depends on both density and moisture content. Hohle (2001) recommended using the simple approximation

$H = (5.32 – 6.02 \cdot y)$ kWh/kg,

where H is theoretical energy output and y is the moisture in the wood (percent). It is assumed throughout that 1 m^3 of dry wood has a mass of 423 kg, and that half of the mass is carbon. This gives 0.211 tonnes of carbon per m^3, or 0.774 tonnes of CO_2 per m^3 of wood used as fuel.

Sjølie and Solberg (2009) reported that pellets are 8 percent moisture and 92 percent dry wood.

With the assumed moisture content and density, 1 kg of wood represents $2.175 \cdot 10^{-3}$ m^3 of raw material. Hence, the energy output per cubic meter is

$H = ((5.32 – 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3}))$ kWh/m^3.

However, Sjølie and Solberg (2009) also reported that 10 percent of the pellets produced have to be used to reduce the moisture content to 8 percent. In other words, 1.11 m^3 of wood is required to produce pellets with the same theoretical energy content as 1 m^3 of wood with a moisture content of 8 percent. Hence, the theoretical energy output from 1 m^3 of wood is

$H= ((5.32 – 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \cdot (1/1.11)$ kWh/m^3.

With an assumed efficiency ratio of 35 percent, the final energy output per cubic meter of wood will be

$H_e = 0.35 \cdot ((5.32 – 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \cdot (1/1.11)$ kWh/m^3 = 701 kWh/m^3.

In other words, 1 m^3 of wood processed to pellets provides 701 kWh of energy when used for electricity production in a coal-fired power plant with 35 percent energy efficiency.

As regards fossil CO_2 emissions during processing, Sjølie and Solberg (2009) looked at two cases: one where they assumed that BioWood uses Norwegian hydropower, which does not generate CO_2 emissions, and one where they assumed that marginal power is imported and therefore mainly coal based. In practice, the truth probably lies somewhere between these two cases. I have therefore used the average of the two figures, which means that the emissions related to pellet processing are 224 tCO_2/GWh.

On the basis of the work of Hartmann and Kaltschmitt (1999), Sjølie and Solberg (2009) assumed that life-cycle emissions from a coal-fired power plant are 1167 tonnes CO_2/GWh. However, Hartmann and Kaltschmitt (1999) suggested this figure under the assumption that the power plant's efficiency was 43.2 percent, while Sjølie and Solberg (2009) used the same figure when the power plant's efficiency was 35 percent. Because of this inconsistency, I have based my assumptions on the work of Weisser (2007), and assumed that life-cycle CO_2 emissions from a coal-fired power plant with 35 percent efficiency total 931 tCO_2/GWh. Subtracting fossil CO_2 emissions of 224 tCO_2/GWh from pellet production, I find that the net reduction in fossil CO_2 emissions is 707 tCO_2/GWh.

Taking into account that the energy output is 701 kWh/m^3, I find that using 1 m^3 of pellets instead of coal in a power plant can eliminate 0.496 tonnes of fossil CO_2 emissions.

1.4 Sensitivity analysis with regard to the decomposition rate of deadwood

On the basis of the work of Liski et al. (2005), it is assumed that deadwood decomposes at the rate shown in Figure S1. Natural dead biomass decomposes rather more slowly than harvest residues because natural deadwood also contains tree trunks, which break down more slowly than branches, tops and roots. In the reference case, 75 percent of all harvest residues and 70 percent of natural deadwood decomposed in 50 years. In the following, I present a number of sensitivity simulations with regard to these assumptions. The model simulations presented in sections 3.2 and 3.3 of the article are redone, now assuming different rates of decomposition.

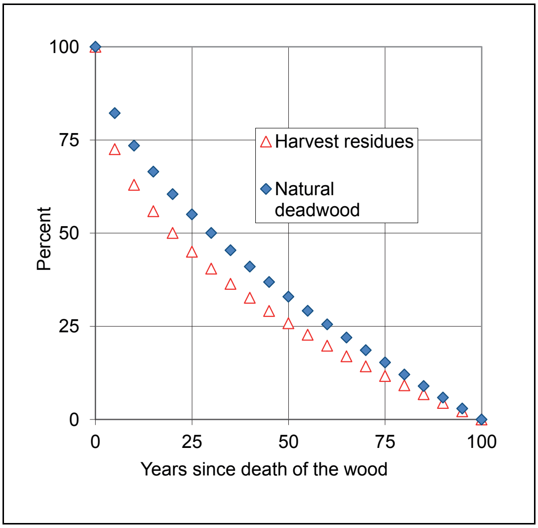

Fig. S1 Remaining share of wood after natural death or clear-cutting. The symbols show the proportion of the wood that has not decomposed at the given time

The share of natural deadwood and harvest residues that has not decomposed after t years is given by equation (11). To test the sensitivity of the underlying assumptions, both higher and lower values of the parameters δ_{Ft} and δ_{Nt} are considered; see Table S3.

Table S3 Parameters δ_{Nt} and δ_{Ft} in the cases considered

	Years for the decomposition of 50 percent of residues	δ_{Ft}	Years for the decomposition of 50 percent of natural deadwood	δ_{Nt}
High rate of decomposition	10	0.301	15	0.365
Reference case	20	0.431	30	0.576
Low rate of decomposition	40	0.756	50	1.000

Table S4 Time to repay the carbon debt if the wood is processed to pellets and replaces coal in power plants—different rates for the decomposition of deadwood*

	Rate of decomposition of natural deadwood		
	High	Reference case	Low
High rate of decomposition of residues	185	195	215
Reference case (residues)	175	190	205
Low rate of decomposition of residues	160	170	190

Table S5 Time to repay the carbon debt if the wood is processed to second-generation liquid biofuels and replaces liquid fossil fuels—different rates for decomposition of deadwood

	Rate of decomposition of natural deadwood		
	High	Reference case	Low
High rate of decomposition of residues	335	355	385
Reference case (residues)	320	340	375
Low rate of decomposition of residues	295	315	350

In the reference case, it follows that 50 percent of natural deadwood decomposes within 30 years, whereas it only takes 20 years for 50 percent of the harvest residues to decompose. It is assumed that natural deadwood decomposes more slowly than harvest residues because the former includes long-lasting trunks.

In the case of the high rate of decomposition, it follows that 50 percent of natural deadwood and harvest residues have decomposed after 15 and 10 years, respectively. In the case of the low rate of decomposition, it follows that 50 percent of natural deadwood and harvest residues have decomposed after 50 and 40 years, respectively.

As is evident from Tables S4 and S5, payback times are significantly lower if a high rate of decomposition of natural deadwood is combined with a low rate of decomposition of harvest residues. However, a case where natural deadwood decomposes more rapidly than harvest residues is unlikely (Storaunet and Rolstad 2002).

2 Single-harvest analyses vs. multiple-harvest analyses

The Manomet report (2010) presented an analysis of the carbon debt generated by a single-harvest event and the corresponding payback time. In this section, it is demonstrated that the payback time determined from such a single-harvest analysis is much shorter than the payback time determined from analysis of a series of subsequent harvest events.

As an example, consider a forest with 19 parcels. All the parcels have the same size and dynamic properties as the standard parcel described in section 1.2 of this supplement and in section 2 of the article. Assume furthermore that parcel #1 was harvested in 1915 and that the forest owner, in a harvest scenario, sticks to a rotation period of 95 years. Consequently, this parcel was ready for harvest in 2010. Furthermore, parcel #2 was last harvested in 1920 and therefore matures in 2015, parcel #3 matures in 2020, and so forth. If the parcels are harvested at these points in time, they will again mature in 2105, 2110, 2115, and so forth, respectively.

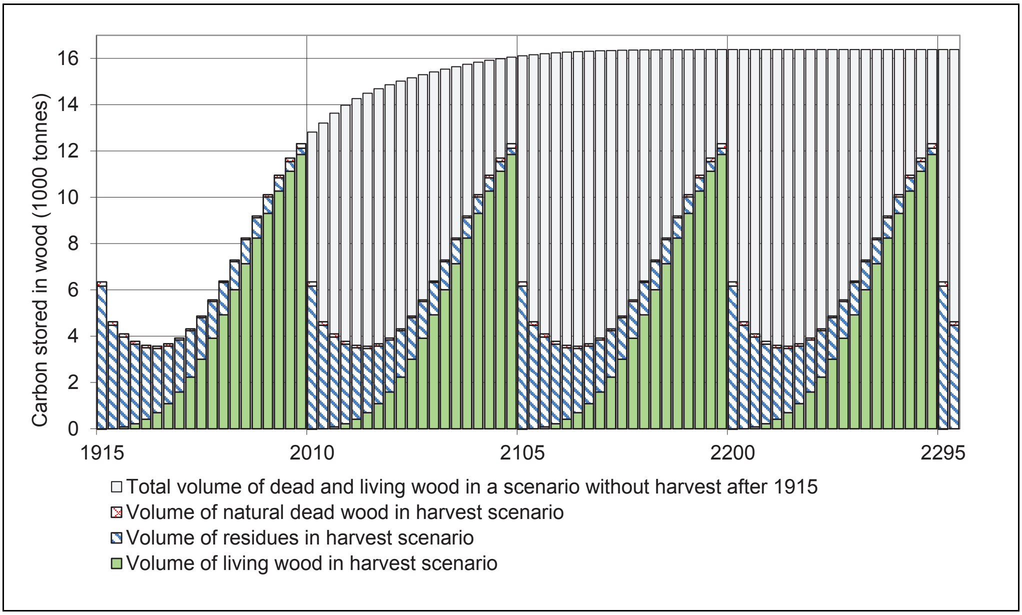

Fig. S2 The development of stock of carbon stored in dead and living wood in parcel #1, both in the case with clear-cutting in 2010, 2105, 2200, and 2295, and in that without harvest after 1915

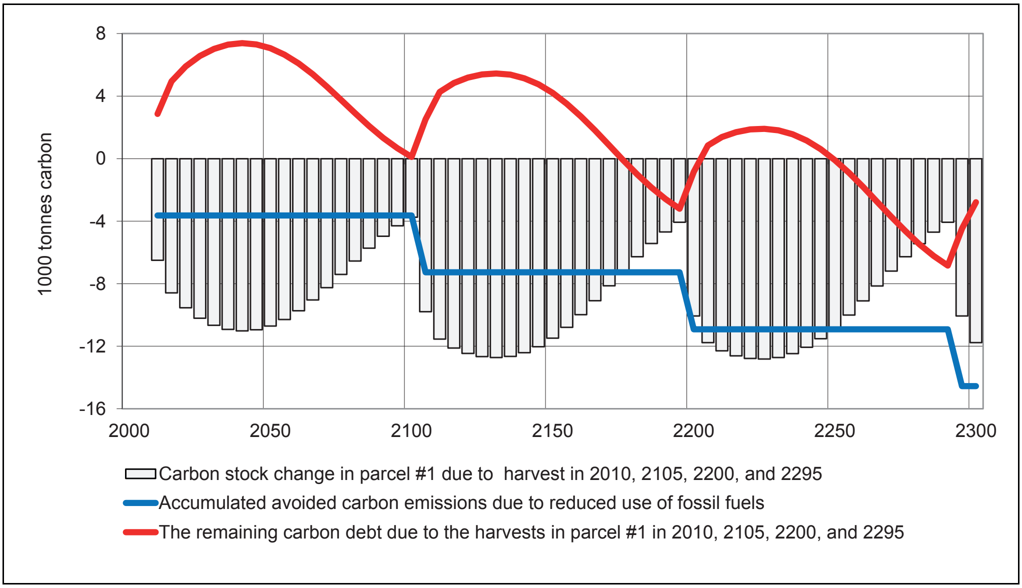

Fig. S3 Consequences of harvest in parcel #1 on this parcel's carbon stock, the accumulated reduction in fossil carbon emissions, and the remaining carbon debt

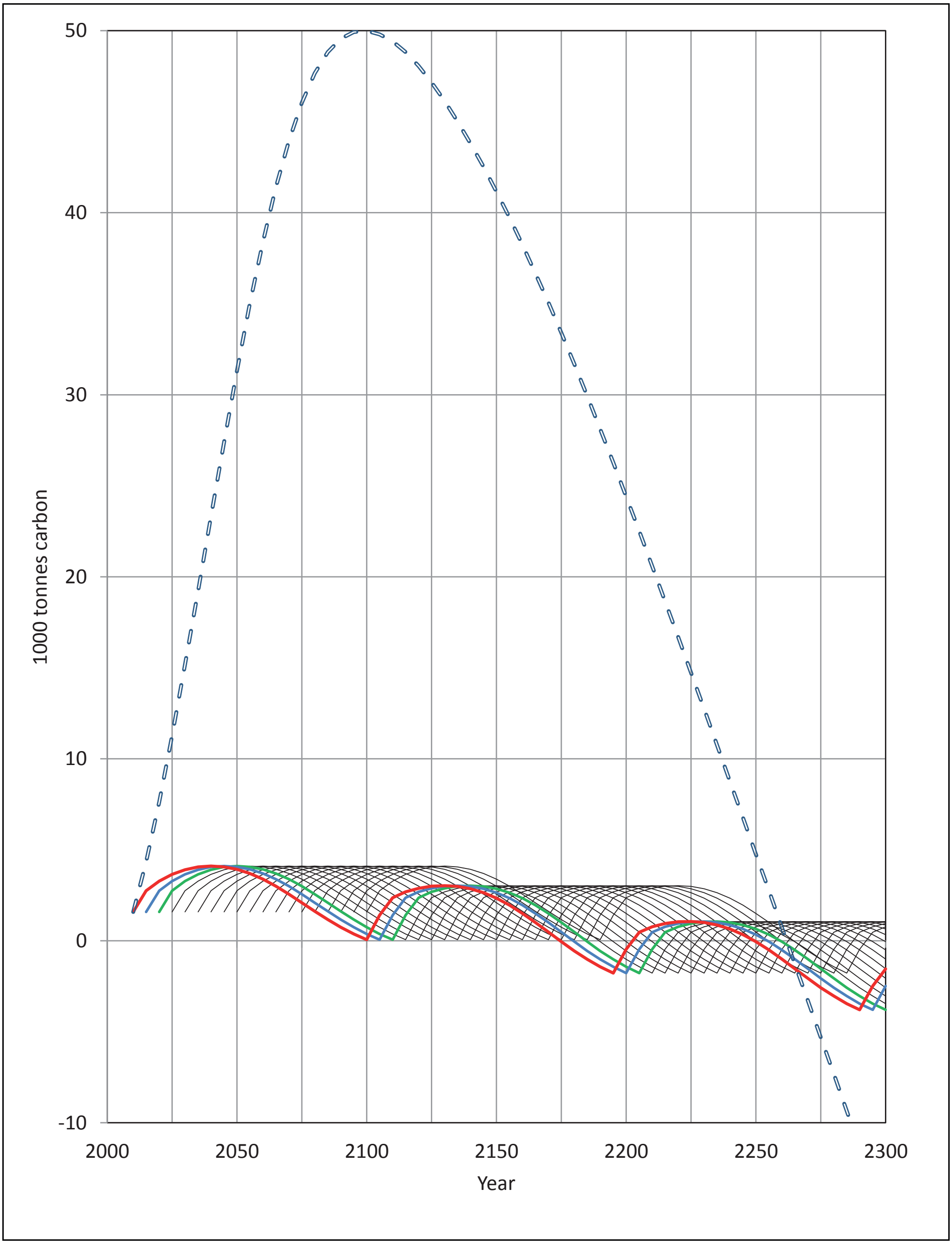

Fig. S4 The multi-wave-shaped curves show the development of the remaining carbon debt generated from the harvesting of 19 parcels as they subsequently mature. The total remaining carbon debt is given by the broken blue curve

Figure S2 shows the development of the volume of carbon stored in dead and living wood in parcel #1 in two cases. The colored columns show the case where clear-cutting and harvest of the trunks took place in 2010, and will also take place in 2105, 2200, and 2295. The gray columns, standing behind the colored columns, show the development if harvest does not take place after 1915.

It is evident from Figure S1 that harvesting means that less carbon is stored in the parcel. This drop in the parcel's carbon stock due to harvest is also illustrated with the gray columns in Figure S3. The lengths of the gray columns in Figure S3 are equal to the apparent parts of the gray columns in Figure S1.

For simplicity, it is in this example assumed there is no harvest of residues. However, it is assumed that each cubic meter of wood harvested means that 0.5 tonnes of fossil CO_2 emissions, or 0.14 tC, is avoided. Each parcel provides 26 900 m^3 of wood at each harvest. Hence, with the assumptions made, 3600 tonnes of carbon emissions are avoided for each harvest; see the blue line in Figure S3. The blue curve takes a new step down at the time of each harvest and measures the accumulated reduction in carbon emissions due to the harvests in parcel #1.

The remaining carbon debt from the harvests of parcel #1 is equal to the vertical distance between the blue line and the bottom of the gray columns in Figure S3; see the red curve. Note that the carbon debt of the single harvest event taking place in 2010 is fully repaid by 2105, that is, after 95 years.

Consider next Figure S4. The red curve from Figure S3 is reproduced here. Note, however, that the scale on the vertical axis is different. Moreover, Figure S4 shows the carbon debt of the harvest that will take place in the other parcels. For example, the blue curve represents the remaining carbon debt from harvesting of parcel #2. These harvest events take place in 2015, 2110, 2205, and 2300. The carbon debt of harvest taking place in 2015 is also repaid after 95 years, that is, by 2110. Correspondingly, the green curve in Figure S4 represents the remaining carbon debt from harvesting of parcel #3. In the same manner, all black curves represent the remaining carbon debt of corresponding subsequent harvesting of the other 16 parcels in the example forest.

These harvest events imply a permanent harvest level of 26 700 m^3 of wood every five years. The question is then at what point in time will the generated carbon debt of this harvest strategy be fully repaid? To calculate this, I sum (vertically) the remaining carbon debt described by all the 19 wave-shaped curves in Figure S4. This gives the broken blue curve in Figure S4, which thus represents the aggregate remaining carbon debt from the harvest of the entire example forest. Note that the carbon debt is repaid in 2260, that is, there is a payback time of 250 years in this permanent-harvest example compared with a payback time of 95 years in the single-harvest example. This difference underlines that single-harvest analysis does not provide complete answers regarding the consequences of increased harvest levels.

One may perhaps wonder why the payback time here is 250 years, while in the corresponding case studied in sections 3.2 and 3.3 in the article it was found to be 190 years. Recall, however, that in the example studied here, no residues were harvested. This explains the majority of the difference. Moreover, the example studied here compares a situation with no harvest in a certain area with a scenario with harvest in the same area. As will be illustrated in the next section, this also means a somewhat longer payback time.

3 EXTENDING THE AREA HARVESTED

Sections 3.2 and 3.3 considered a case where the large-harvest scenario did not imply an extension of the area harvested. Instead, increased harvest was achieved through adjustments of the length of the rotation cycles. Figure S5 shows the stand age at the time of felling in the two scenarios. In both scenarios, the rotation period stabilizes at a relatively high age.

This section, on the other hand, considers two scenarios where increased harvest does not mean any change in the rotation period for the area already harvested. Instead, a large-harvest scenario means an extension of the area that is harvested.

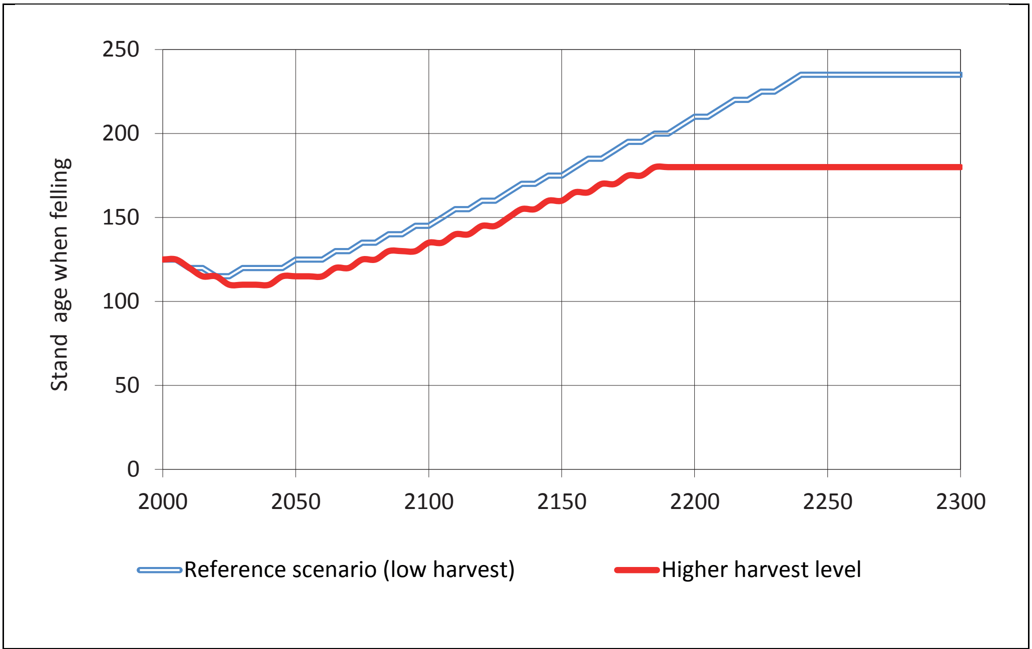

Fig. S5 Stand age at the time of felling in the two scenarios considered in sections 3.2 and 3.3

In the reference scenario, the harvest is 10 Mm^3, as in the case considered in sections 3.2 and 3.3. However, it is assumed that this harvest level is achieved through harvesting a limited area of only 45.5 percent or 34000 km^2 of the forest and a rotation period of 90–130 years. In the reference scenario, there is no harvest outside this area.

To increase the harvest from 10 to 13 Mm^3, an additional area of 10 108 km^2 is harvested. Hence, this section analyzes this limited area only, as the harvest in the rest of the forest is identical in the scenarios considered here.

The considered area has an age distribution at the outset as described in Table S2.

In addition to the reference scenario with *no harvest* in this area, two different harvest scenarios are considered in this section, one *conservative* and one *optimistic*. In both harvest scenarios, the annual harvested volume is 3 Mm^3. The *optimistic* harvest scenario is motivated by claims that harvest is an opportunity to replace sparse forests with more productive forests.

The *optimistic* harvest scenario assumes that after clear-cutting and replanting, the density of trees in the harvested parcels is 25 percent higher than the previous density of the standard parcels as described in section S1. In other words, in the *optimistic* scenario, the stock of trunks and other living biomass in any parcel that has undergone clear-cutting and replanting in 2010 or later is 25 percent higher than would have been the case if the regeneration of the parcels had followed the path described in Figure 1. Hence, in the *optimistic* scenario, the development of the parcels' living biomass can be described as

$$B_{it} = \begin{cases} B(\tau_i(t)) \text{ if } \tau_i(t) > t - 2010, \\ (1+\varepsilon)B(\tau_i(t)) \text{ if } \tau_i(t) \leq t - 2010, \end{cases} \quad (12)$$

where the function $B(\tau_i(t))$ is described in equation (8) - (9) and it is assumed that the parameter $\varepsilon = 0.25$.

In the *conservative* harvest scenario, the productivity of the parcels follows the path described in Figure 1, both before and after clear-cutting and replanting. Said differently, the parameter $\varepsilon = 1$.

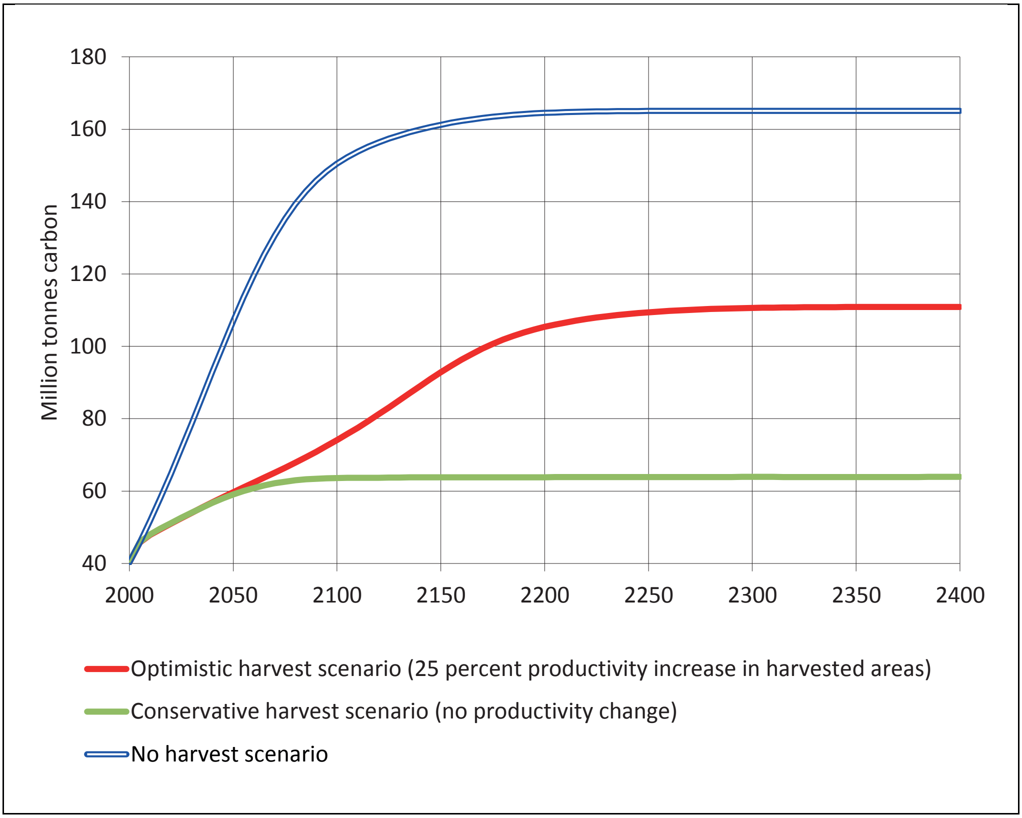

Fig. S6 Carbon stored in dead and living biomass in the area of 10 108 km^2

The results of these simulations are described in Figures S6 and S7. In the *no harvest* scenario, the stock of carbon stored in dead and living biomass increases until approximately the year 2200. The stock then stabilizes, i.e., a new steady state is reached.

In the *conservative* harvest scenario, the stock of biomass stabilizes at a lower level; see Figure S6. In the *optimistic* harvest scenario, the stock of biomass stabilizes at a higher level than in the conservative scenario. This is because of the assumption that areas where clear-cutting has taken place will experience 25 percent higher productivity than they had in the previous rotation period. Hence, as the parcels in the considered area are successively felled, they enter a phase with more rapid regrowth and stabilization at a higher level.

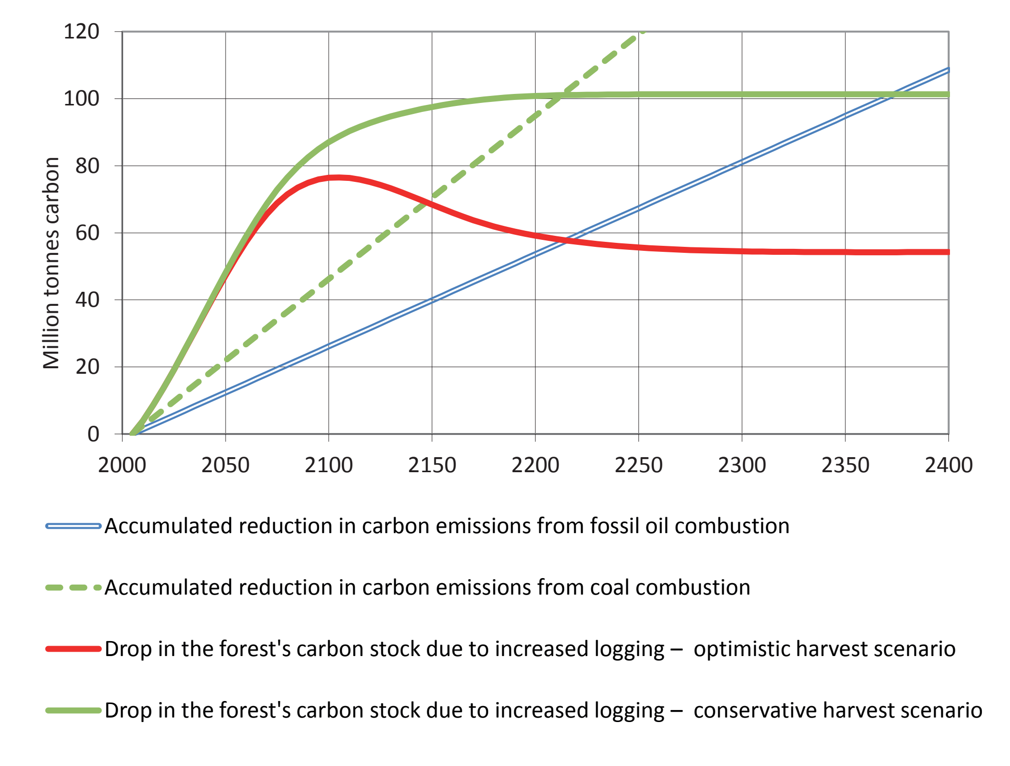

Fig. S7 The two straight lines show the accumulated reductions in CO_2 emissions achieved from the reduced combustion of fossil fuels due to the increased supply of bioenergy. The curves show to what extent the forest's carbon stock is reduced as the harvest is increased.

Again the question is how large volumes of CO_2 emissions from fossil energy can be eliminated by increasing the harvest. This is illustrated in Figure S7. The two straight lines are identical to the straight lines in Figure 4 in the article because we still consider the substitution effect of 3 Mm^3 of wood (or 3.6 Mm^3 including residues). Hence, the green broken line in Figure S7 shows the reduced emissions from coal burning (accumulated) when pellets replace coal in power plants. Correspondingly, the double line in Figure S7 shows the reduced CO_2 emissions from combustion of liquid fossil fuels (accumulated) due to increased supply of liquid biofuels from wood.

A comparison of Figures S7 and 4 shows that the net effect of increased harvest does not change substantially when increased harvest is achieved through expanding the harvested area instead of reducing the average length of the rotation period. Expansion of the harvested area implies that the carbon debt is repaid somewhat later than was the case when reducing the length of the rotation period. In the *optimistic* scenario, as expected, the carbon debt is repaid sooner than in the *conservative* scenario. Table S6 provides a summary of the calculated payback times.

Table S6 Time to repay the biofuel carbon debt from increased harvest in a boreal forest (years)

	Increased harvest through reduced length of the rotation cycles	Increased harvest through extension of the harvested area—*conservative scenario**	Increased harvest through extension of the harvested area—*optimistic scenario*
Wood fuels replace pellets in coal-fired power plants	190	205	135
Second-generation wood fuels replace fossil diesel	340	360	205

* The *optimistic* harvest scenario assumes that after clear-cutting and replanting, the density of trees in the harvested parcels is 25 percent higher than the previous density of the standard parcels. See details in the text.

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Essay 5
Quantifying the global warming potential of CO_2-emissions from wood fuels

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Essay 5

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Quantifying the global warming potential of CO_2 emissions from wood fuels

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Abstract

Recent studies have introduced the metric GWP_{bio}, an indicator of the potential global warming impact of CO_2 emissions from biofuels. When a time horizon of 100 years was applied, the studies found the GWP_{bio} of bioenergy from slow-growing forests to be significantly lower than the traditionally calculated GWP of CO_2 from fossil fuels. This result means that bioenergy is an attractive energy source from a climate mitigation perspective. The present paper provides an improved method for quantifying GWP_{bio}. The method is based on a model of a forest stand that includes basic dynamics and interactions of the forest's multiple carbon pools, including harvest residues, other dead organic matter, and soil carbon. Moreover, the baseline scenario (with no harvest) takes into account that a mature stand will usually continue to capture carbon if not harvested. With these methodological adjustments, the resulting GWP_{bio} estimates are found to be two to three times as high as the estimates of GWP_{bio} found in other studies, and also significantly higher than the GWP of fossil CO_2, when a 100-year time horizon is applied. Hence, the climate impact per unit of CO_2 emitted seems to be even higher for the combustion of slow-growing biomass than for the combustion of fossil carbon in a 100-year time frame.

Keywords: bioenergy, boreal forests, carbon, forests, GWP_{bio}, multiple carbon pools, wood fuels

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Introduction

Global warming potential (GWP) is a frequently used metric when the climate impacts of greenhouse gases (GHGs) need to be compared. GWP quantifies the cumulative potential warming effect of a pulse of GHGs over a specified time frame, taking its absorption of infrared radiation and atmospheric lifetime into account. GWP is a relative measure and the GWP of CO_2 is given the ratio 1.

Traditionally, bioenergy has been considered to be carbon neutral because the released carbon is absorbed by the harvested crops' regrowth. Thus, CO_2 released from the combustion of bioenergy has been given a GWP of zero in most LCA analyses. For the same reason, no country imposes taxes on CO_2 emissions from the combustion of bioenergy, and firms included in the European Union emissions trading market are not committed to acquiring and surrendering allowances for CO_2 emissions from the combustion of bioenergy.

There is now increasing agreement that biofuels from forests should not be considered to be carbon neutral because there is a significant time lag between harvesting and regrowth; see for example Chum *et al.* (2012), Haberl (2013), Haberl *et al.* (2012a, b), Holtsmark (2013a, b), Hudiburg *et al.* (2011), Schulze *et al.* (2012), Searchinger *et al.* (2009). An article by Fargione *et al.* (2008) triggered different studies that estimated the length of the carbon debt payback period of biofuels from slow-growing forests (McKechnie *et al.*, 2011; Zanchi *et al.*, 2011; Holtsmark, 2012; Bernier & Paré, 2013; Dehue, 2013; Jonker *et al.*, 2013; Lamers & Junginger, 2013).

At the same time, Cherubini *et al.* (2011a) introduced a new concept labeled GWP_{bio}, which was proposed as an indicator of the net potential warming impact of CO_2 released by the combustion of biomass when it is taken into account how the regrowth of harvested trees recaptures the amount of CO_2 that was released by the combustion of the harvest. Taking the time profile of this regrowth into account, the calculated lifetime of a pulse of CO_2 from bioenergy was found to be shorter than the lifetime of a pulse of CO_2 from fossil fuels. Consequently, it seems reasonable that the potential warming impact of CO_2 from bioenergy is smaller than the potential warming impact of CO_2 from fossil fuels. With a time horizon of 100 years, Cherubini *et al.* (2011a) found GWP_{bio} to be 0.43 when they considered a stand of a slow-growing forest that was harvested at an age of 100 years. With shorter rotations, they found lower estimates of GWP_{bio}.

Later Cherubini *et al.* (2011b, 2012), Bright *et al.* (2012), Guest *et al.* (2012), and Pingoud *et al.* (2011) presented estimates of GWP_{bio} in the interval 0.34–0.62 when slow-growing forest stands were considered. The fact that these estimates are significantly below 1.0 indicates that

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bioenergy from slow-growing forests 'becomes an attractive climate change mitigation option' (Cherubini *et al.*, 2011b, p 65).

However, an examination of the above-mentioned papers reveals some serious weaknesses with regard to their method for modeling and calculating GWP_{bio}. Bright *et al.* (2012), Cherubini *et al.* (2011a, b, 2012) and Pingoud *et al.* (2011) applied models of a forest stand that did not include the harvest's effects on the dynamics of important carbon pools such as harvest residues, natural deadwood, and soil carbon. Moreover, only Pingoud *et al.* (2011) included a realistic baseline scenario. The other studies made the simplifying assumption that, if not harvested, there is no further growth and accumulation of carbon in a mature stand. Guest *et al.* (2012) did include harvest residues in their analysis, but they did not include natural deadwood or effects on soil carbon, and they did not construct a realistic baseline scenario.

The main purpose of this paper is to present an improved method for modeling and quantifying the potential warming impact of CO_2 from the combustion of biomass from slow-growing forests (GWP_{bio}). The methodological improvements are related to the model of the considered forest stand and the construction of a realistic baseline scenario (Helin *et al.* 2012, Holtsmark, 2013a, b).

Firstly, the proposed method applies a no-harvest baseline scenario that takes into account that stands are usually considered mature and therefore harvested before growth has culminated (Faustmann, 1849; Samuelson, 1976; Scorgie & Kennedy, 1996; Holtsmark *et al.*, 2012). At this point, note that when this paper uses the expression 'a mature stand', it refers to a stand that is considered ready for harvesting. The Faustmann rule states that a stand should be harvested before the point in time when marginal growth drops below average growth; see Holtsmark, 2012, 2013b for further details.

Secondly, the proposed method includes modeling the dynamics of the forest stand's main carbon pools, including harvest residues, the pool of natural deadwood as well as all parts of growing trees such as branches, tops, stumps, and roots in addition to the stems. The effects of harvesting on the pool of soil carbon are also modeled (Buchholz *et al.*, 2013). Including the forest stand's different carbon pools in the model is important as the dynamics of these pools, which are influenced by harvesting, determine the path of the net carbon flux between the considered forest stand and the atmosphere. The resulting GWP_{bio} ratios will be misleading if only the carbon flux generated by the regrowth of the harvested trees is taken into account, while not taking into account how other carbon fluxes between the considered stand and the atmosphere are altered.

To show the importance of the methodological improvements, the paper also presents some numerical examples. When a 100-year time horizon was applied to a forest stand of age 100 years, the resulting GWP_{bio} estimate was found to be 1.54, i.e., two to three times as high as the estimates of GWP_{bio} found in the above-mentioned studies, and significantly higher than 1. This result is not very sensitive to the considered stand's age. If harvest instead takes place when the stand's age is for example 70 years or 200 years, the GWP_{bio} was found to be 1.79 and 1.38, respectively. Hence, to the extent that GWP_{bio} is a useful index, bioenergy from slow-growing forests is not as attractive from a climate perspective as concluded in some of the above-mentioned studies.

The outline of the paper is as follows. The next section presents a model of a forest stand and all parameter values. Thereafter, the applied model for the accumulation of carbon in the atmosphere is described before the proposed method for calculating GWP_{bio} is presented. The results section consists of three parts. First, the basic results are presented. A number of sensitivity analyses then follow, and a set of model simulations are presented in a subsection to show the effects of the different methodological simplifications made in the studies by Cherubini *et al.* (2011b), Guest *et al.* (2012), and Pingoud *et al.* (2011). It is shown that, with corresponding simplifications of the model applied in this paper, their results are reproduced. Finally, there is a section discussing the results and concluding.

Materials and methods

The model of the forest stand

Figure 1 provides an overview of the basic properties of the model of the considered forest stand. The basis for the estimation of GWP_{bio} is a comparison of the time profile of the forest stand's total carbon stock in the harvest scenario (Fig. 1a) and in the no-harvest scenario (Fig. 1b) and the corresponding net flux of CO_2 between the stand and the atmosphere. As a starting point, it was assumed that the stand's age at time of harvest (t = 0) is 100 years, with a total carbon stock of 162 tC (before harvesting). In the harvest scenario, all stems of living trees are removed from the stand at time t = 0 with subsequent combustion giving rise to a pulse of CO_2 corresponding to the amount of carbon contained in the stems (39 tC). Hence, after harvesting, the stand stores 123 tC; see Fig. 1a. A case including the use of harvest residues was also considered, giving rise to a correspondingly higher emission pulse at time t = 0 and correspondingly smaller subsequent emissions from the decomposition of residues. After harvesting, new trees start growing; see the hatched and cross-hatched areas in Fig. 1a. Residues left on the forest floor decompose; see the black area. Moreover, natural deadwood (NDOM) that was present in the stand at the time of harvesting also gradually decomposes, while new naturally dead biomass is generated; see the dotted area in Fig. 1a.

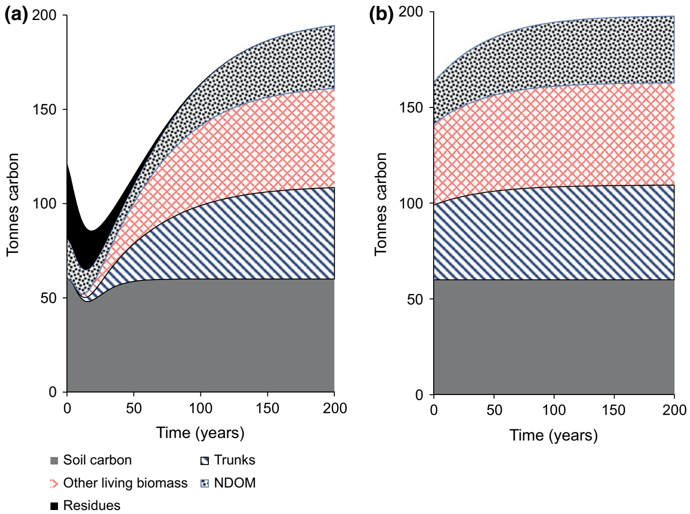

Fig. 1 Development of the carbon pools of a single stand in a case where no residues were harvested. (a) The harvest scenario. (b) The no-harvest scenario.

With regard to the dynamics of the soil's carbon pool, it was assumed that harvesting results in some years with a net release of carbon from the soil. Thereafter, the soil's carbon pool gradually returns to its original state; see Fig. 1a.

The development of the stand's carbon stock in the no-harvest baseline scenario is shown in Fig. 1b. The starting point is that the stand's age is 100 years at $t = 0$. Hence, at time $t = 0$ in the no-harvest scenario, the sizes of the carbon pools are the same as at time $t = 100$ in the harvest scenario, cf. Fig. 1a and b. Moreover, in the no-harvest scenario, there is continued forest growth after $t = 0$ with a corresponding continued accumulation of natural deadwood. In the no-harvest scenario, the soil's carbon pool is assumed to be constant over time.

There is great uncertainty about the likely development of the carbon stock of an old stand (Helin *et al.* 2012). However, in accordance with, e.g., Luyssaert *et al.* (2008), I assumed continued accumulation of carbon even in old stands. As this is an uncertain part of the scenario, a sensitivity analysis is carried out with a significantly smaller accumulation of carbon in older stands.

In addition to the case where the stand age is 100 years at time of harvest, the section with sensitivity analyses presents results of simulations where the stand's age is 70 and 200 years at time of harvest, with corresponding adjustments of the dynamics of the carbon pools. For example, if harvest takes place when the stand's age is 200 years, the growth and accumulation of biomass in the baseline no-harvest case is almost negligible.

A detailed description of the construction of the numerical model follows below. The basic building block in the model is the growth function for tree trunks:

$$G(\tau) = v_1(1 - e^{-v_2\tau})^{v_3}, \quad (1)$$

where $G(\tau)$ is the timber volume of a forest stand of 1 ha (measured in tons of carbon per ha, tC ha^{-1}), whereas τ is the stand's age and v_1, v_2, and v_3 are parameters. This is a functional form frequently used in the literature; see for example Asante & Armstrong (2012), and Asante *et al.* (2011). The value of the parameters v_2 and v_3 are based on Cherubini *et al.* (2011b), and Holtsmark (2013b). The scale parameter v_1 is calibrated, so that, at stand age 100 years, the stand's volume of trunks is 194 m^3 ha^{-1}. This is in agreement with results of simulations using the Norwegian forest model AVVIRK-2000 (see Eid & Hobbelstad, 2000), which indicate that harvesting in a typical Norway spruce forest would yield an average harvest of 194 m^3 ha^{-1}.

For all calculations, the starting point is that, at time $t = 0$, the stand age is τ_h and the stand is considered to be mature. In the harvest case, the harvesting takes place at time $t = 0$, and regrowth restarts along the path described by $G(t)$ whereas, in the baseline scenario, there is no harvest and the forest growth continues along the path described by $G(\tau_h + t)$ as defined in (1).

On average, trunks are assumed to constitute a proportion $\theta = 0.48$ of total living biomass (Løken *et al.*, 2012). Hence, the total living biomass $B(\tau)$ in a stand is:

$$B(\tau) = \frac{1}{\theta}G(\tau). \quad (2)$$

Next, consider the dynamics of the pool of harvest residues. At the time of harvesting, the stock $G(\tau_h)$ of stems is removed from the stand. In addition, a proportion σ of the residues is harvested. Hence, the total harvest is

$$E(\tau_h, \sigma) = G(\tau_h) + \sigma(B(\tau_h) - G(\tau_h)). \quad (3)$$

It will be assumed here that the harvested biomass is used as energy immediately after harvesting. Hence, in the harvest scenario, there will at time t = 0 be a pulse emission equal to E(τ_h, σ).

In the harvest case, an amount of residues, $(1-\sigma)(B(\tau_h)-G(\tau_h))$, is generated at time t = 0, while there are no harvest residues in the baseline scenario. Hence, only in the harvest scenario is there an amount of harvest residues on the forest floor as described by the function:

$$D_R(t, \tau_h, \sigma) = e^{-t\omega}(1-\sigma)(B(\tau_h)-G(\tau_h)), \quad (4)$$

where ω is the annual decomposition rate for dead organic matter. Based on the results and the discussion in Liski *et al.* (2005), this parameter was set to 0.04. As it is known that decomposition rates differ greatly between different components of the trees, it would have improved the model to let the speed and time profile of decomposition depend on the type of residues and NDOM components (Repo *et al.*, 2011). However, sensitivity simulations were carried out that showed that the results are relatively insensitive to the size of this parameter; see the results section. Hence, although the results' sensitivity with respect to different decomposition rates for different residue components has not been tested for, this indicates that the assumed speed of decomposition in general is not very important to the results.

Let subscript H refer to the harvest scenario, whereas subscript 0 refers to the reference scenario without harvesting. Consider the pool of natural deadwood, $D_{Ni}(t)$, i = H, 0, which also decomposes at the rate ω. Define the parameters δ_0 = 1 and δ_H = 0. The NDOM pool develops as follows:

$$D'_{Ni}(t) = \beta B(\delta_i\tau_h + t) - \omega D_{Ni}(t), i = H, 0, \quad (5)$$

where β is a positive parameter and the term $\beta B(\cdot)$ represents litterfall, whereas $\omega D_{Ni}(t)$ represents decomposition. This means that the amount of NDOM generated at time k that is left at time t is $e^{-(t-k)\omega}\beta B(k)$. Hence, the time profile of the stock of NDOM is as follows:

$$D_{Ni}(t) = e^{-t\omega}D_0 + e^{-t\omega}\int_0^t e^{k\omega}\beta B(\delta_i\tau_h + k)dk, i = H, 0, \quad (6)$$

where D_0 represents the amount of DOM in the stand at time t = 0. Thus, the first term on the right-hand side represents the amount of DOM that remains from the previous rotations, and the second term on the right-hand side represents NDOM generated after time t = 0. Based on Asante & Armstrong (2012) and Asante *et al.* (2011), the parameter β was set to 0.01357.

Next, consider the dynamics of soil carbon. An important question is the extent to which harvesting triggers the release of carbon from soil. As emphasized by Fontaine *et al.* (2007), Friedland & Gillingham (2010), Jonker *et al.* (2013), Kjønaas *et al.* (2000), and Nilsen *et al.* (2008), the accumulation and possible release of carbon from the soil are complicated processes and there is a high degree of uncertainty here. However, according to field experiments reported by Olsson *et al.* (1996), the loss of carbon after clear-cutting in a spruce forest could be substantial. Olsson *et al.* (1996) found that, 15 years after clear-cutting, the net loss of soil carbon from a spruce site is within the range 9–15 tC ha^{-1}. They found that in mature forests most of the soil carbon has been recaptured.

The following model of soil carbon was therefore constructed:

$$S_i(t) = S_0 - (1-\delta_i)s_1e^{s_2t}\left(1-e^{s_2t}\right)^{s_3}, i = H, 0,$$

where S_0 is the constant amount of soil carbon in the stand in the no-harvest case, whereas s_1, s_2, and s_3 are parameters. The parameter values are given in Table 1. They were calibrated to give a maximum soil carbon loss of 12 tC ha^{-1} 15 years after harvesting. After 15 years, the stand's soil carbon pool was assumed to gradually increase back to its original state, see Fig. 1. Although not important for this analysis, the fixed baseline stock of soil carbon, S_0, was set to 60 tC ha^{-1}. This corresponds to a mean of the estimates of the amount of carbon contained in the organic part of the soil found by de Wit & Kvindesland (1999).

It should be noted here that it was assumed that forest residue removal does not amplify the loss of soil carbon after harvest and does not reduce future growth. This is probably somewhat optimistic (Johnson & Curtis, 2001).

The stand's total carbon stock, labeled $\Omega_i(t)$, includes the carbon pool of all living biomass $B(t)$, the pool of harvest residues D_R (t), the NDOM pool $D_{Ni}(t)$ and soil carbon $S_i(t)$:

$$\Omega_i(t) = B(\delta_i\tau_h + t) + (1-\delta_i)D_R(t) + D_{Ni}(t) + S_i(t), i = H, 0. \quad (7)$$

To sum up, in the harvest scenario, there will be a pulse emission $E(\tau_h, \sigma)$ at time t = 0, followed by a phase of regrowth and carbon capture, leading to a net flux from the stand to the atmosphere following the path of $-\Omega'_H(t),\ t \in (0, \infty)$. In the baseline no-harvest scenario, there will be no pulse emission at t = 0, but continued growth will lead to a negative net flux following the path of $-\Omega'_0(t),\ t \in (0, \infty)$. All parameter values are listed in Table 1. $\Omega'_i(t)$ represents the time derivative of $\Omega_i(t)$, which is the net carbon flux from the atmosphere to the stand due to the stands's growth as well as the release of soil carbon and the release of CO_2 from the decomposition of harvest residues and NDOM.

Table 1 Parameter values

y_0	0.217
y_1	0.259
y_2	0.338
y_3	0.186
α_1	172.9
α_2	18.51
α_3	1.186
β	0.01357
ω	0.04
v_1	103.067
v_2	0.0245
v_3	2.6925
δ_H	0
δ_{NH}	1
s	0.48
s_1	−113.5
s_2	−0.09
s_3	3.003

Accumulation of carbon in the atmosphere

With regard to the fraction of an initial pulse of CO_2 at time $t = 0$, that remains in the atmosphere at time t, labeled $y(t)$, the following function is applied:

$$y(t) = y_0 + \sum_{i=1}^{3} y_i e^{-t/\alpha_i}, \tag{8}$$

where α_i and y_i are parameters. This decay function is based on Joos & Bruno (1996), Joos *et al.* (1996), and Joos *et al.* (2001), labeled the Bern 2.5CC carbon cycle model. It takes into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere and the sea. For example, the profile of the solid single-lined curve in Fig. 2 describes the remaining proportion at time t of the CO_2 pulse generated at time $t = 0$ in the harvest scenario. However, the Bern 2.5CC model is also applied to fluxes of CO_2 generated by the stand's growth, as well as the release of CO_2 due to decomposition of NDOM and harvest residues left on the forest floor; see further details below.

Let $A_H(t)$ be the amount of atmospheric carbon at time t that is caused by the harvest with subsequent combustion of the biomass and the stand's regrowth, while $A_0(t)$ is the amount of atmospheric carbon in the no-harvest case, i.e., taking continued growth into account. We then have:

$$A_H(t) = E(\tau_h, \sigma) \cdot y(t) - \int_0^t \Omega'_H(k) y(t-k) dk, \tag{9}$$

$$A_0(t) = -\int_0^t \Omega'_0(k) y(t-k) dk, \tag{10}$$

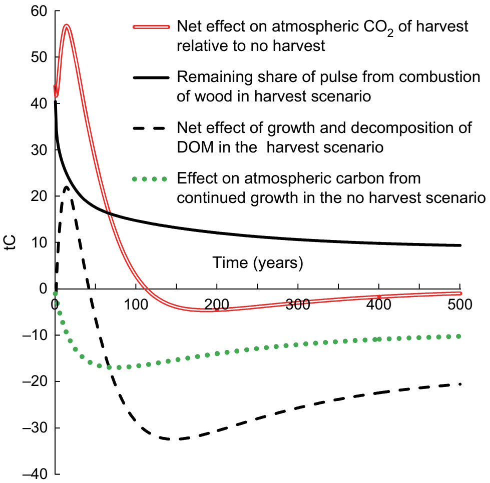

Fig. 2 Development of atmospheric carbon released from the forest stand's main carbon pools.

where $E(\tau_h, \sigma)$ represents the pulse emission at time $t = 0$, see (3). As all variables are measured with regard to their carbon content, this pulse is equal to the harvested biomass $E(\tau_h, \sigma)$, which depends on the stand age and the proportion of residues harvested.

The terms on the right-hand side of (9) and (10) are illustrated in Fig. 2 in a case without any residues harvested. The solid single-lined curve depicts the first term on the right-hand side of (9), i.e., the remaining share at time t of the pulse emission from combustion of the harvest at time $t = 0$.

The dashed curve in Fig. 2 represents the second term on the right-hand side of (9), i.e., the accumulated net effect on atmospheric carbon of decomposition of harvest residues left on the forest floor and NDOM (release of carbon) in addition to the stand's regrowth (carbon capture) and net release of soil carbon. In the first phase after harvesting, the decomposition of residues and NDOM dominates the effect of regrowth. Hence, the dashed curve is upward sloping, corresponding to the net release of CO_2 from the stand. Later on, when a large proportion of the residues have decomposed, regrowth dominates and the dashed curve becomes downward sloping, which means that there is net accumulation of carbon in the stand.

The dotted curve in Fig. 2 represents the right-hand side of Eqn (10), i.e., the accumulated effect on atmospheric carbon of the continued growth and carbon capture in the forest in the no-harvest scenario.

The net effect on atmospheric carbon of harvesting compared with the baseline scenario without harvesting is:

$$A(t) = A_H(t) - A_0(t). \tag{11}$$

The double-lined curve in Fig. 2 depicts the profile of $A(t)$ in a case where no residues were harvested. It is found by vertically adding the dashed and solid lines in Fig. 2 and then vertically subtracting the dotted line in the same diagram. The double-lined curve is above the x-axis during the first 115 years after harvesting. This means that the harvest would result in a higher atmospheric CO_2 concentration in this period compared to a no-harvest case. At $t = 115$, the double-lined curve crosses the x-axis. This means that harvesting would result in lower atmospheric CO_2 when $t \geq 115$, using the no-harvest scenario as the reference point.

Global warming potentials

The concept of global warming potential (GWP) was introduced as a relative measure of how much heat a greenhouse gas traps in the atmosphere compared with the amount of heat trapped by a similar mass of carbon dioxide. Hence, the GWP factor of CO_2 is 1. GWP is commonly calculated over time horizons of 20, 100 or 500 years.The *absolute* global warming potential, $AGWP_{CO_2}(T)$, of a CO_2 pulse $E(\tau_h, \sigma)$ is usually calculated as follows:

$$AGWP_{CO_2}(T) = \int_0^T \alpha_{CO_2}(t) \cdot y(t) E(\tau_h, \sigma) dt, \tag{12}$$

where $\alpha_{CO_2}(t)$ is the radiative forcing effect of CO_2 at time t, T is the applied time horizon, whereas $y(t)$ is the proportion of the emission pulse that is still in the atmosphere at time t, see Eqn (8).

More recently, Cherubini *et al.* (2011a) introduced the concept $AGWP_{bioCO_2}$ which is intended to measure the absolute warming potential of a pulse of CO_2 caused by the combustion of biomass when it is taken into account that harvesting is followed by regrowth of the trees in the forest stand and other dynamic processes triggered by the harvesting. Using the model of a forest stand described above, the appropriate definition of $AGWP_{bioCO_2}$ is then:

$$AGWP_{bioCO_2}(T) = \int_0^T \alpha_{CO_2}(t) \cdot A(t)dt, \tag{13}$$

where $A(t)$, defined in (11), represents the net effect of harvesting on the atmospheric carbon stock, compared with the baseline scenario without harvesting. To measure the *relative* global warming effect of biomass combustion, Cherubini *et al.* (2011a) next defined the $GWP_{bio}(T)$ factor

$$GWP_{bio}(T) = \frac{AGWP_{bioCO_2}(T)}{AGWP_{CO_2}(T)}. \tag{14}$$

The radiative forcing effect of CO_2, $\alpha_{CO_2}(t)$, is expected to decrease over time as the concentration of CO_2 increases. For the sake of simplicity, I will make the approximation that $\alpha_{CO_2}(t)$ is constant over time (see Caldeira & Kasting, 1993). It follows that (14) could be simplified to:

$$GWP_{bio}(T) = \frac{\int_0^T A(t)dt}{\int_0^T y(t)E(\tau_h, \sigma)dt}, \tag{15}$$

where $Y(t)$ and $A(t)$ are defined above. For easier interpretation of the results presented in the next section, recall that the profile of $A(t)$ is described by the double-lined curve in Fig. 2, while the profile of $y(t)E(\tau_h, \sigma)$ is described by the black solid curve in Fig. 2.

Results

Consider the estimates of GWP_{bio} provided in Table 2. Two cases are displayed, one with no residues harvested and one with collection of 25 percent of the residues. A proportion of 25 percent was chosen because that could represent a case in which most of the branches and tops were harvested, while stumps and below ground residues are left in the stand. This study did not consider cases where more than 25 percent of the residues were harvested, because knowledge about the consequences for forest productivity and soil carbon of such harvesting is limited (Helmisaari *et al.*, 2011).

Table 2 Estimates of GWPbio ratios for 20, 100, and 500-year time horizons for different proportions of harvest residues

	TH = 20	TH = 100	TH = 500
No residues harvested	1.92	1.54	0.31
25% of residues harvested	1.65	1.25	0.25

Assuming the stand's age at time of harvest to be 100 years, the GWP_{bio} factor is here estimated to be 1.54 when no residues are harvested (100 years time horizon). If 25 percent of the residues are harvested, GWP_{bio} drops to 1.25.

As mentioned in the introduction, the estimates of GWP_{bio} presented here exceed 1.0, while estimates of GWP_{bio} in earlier studies are significantly below 1.0. For example, when they considered a forest stand that was mature and harvested at a stand age of 100 years, Cherubini *et al.* (2011a, b) found a GWP_{bio} factor of 0.44 and 0.43, respectively. Moreover, when using a time horizon of 100 years, Guest *et al.* (2012) found the GWP_{bio} factor to be 0.62 when all harvest residues were left on the forest floor. And finally, Pingoud *et al.* (2011) estimated the GWP_{bio} factor to be 0.60 when the stand age at felling was 100 years. The discussion section provides a detailed explanation for these differences. It will be shown that implementing different sets of restrictions/simplifications of the model used in this paper means that the model becomes comparable to the models used in the aforementioned studies, and their results are reproduced.

There are various reasons why the estimates of GWP_{bio} found here exceed 1.0, when a time horizon of 100 years was applied. First, the release of CO_2 from the decomposition of the residues left on the forest floor is significant and it comes in addition to the pulse emission generated by the combustion of the harvested stems. Secondly, the dynamics of the pool of carbon stored in natural deadwood are important, and especially the different dynamics of this carbon pool in the harvest scenario compared to the baseline no-harvest scenario. More generally, the harvest scenario is evaluated against a no-harvest baseline scenario. In the baseline scenario, there is continued forest growth although at a declining rate, and there is continued accumulation of dead organic matter. Finally, the release of carbon from the soil after harvesting plays a role, although not a major one.

The results discussed so far relate to a time perspective of 100 years. If a time perspective of 500 years is found to be more relevant than the standard 100 years discussed above, the results become significantly more in favor of wood fuels. For example, in the case with no residues harvested, and with a 500-year time horizon, GWP_{bio} was found to be 0.31; see Table 2. See also Fig. 3, which shows how the GWP_{bio} estimates vary depending on the time horizon. With no residues harvested, GWP_{bio} exceeds 1.0 if the time horizon is

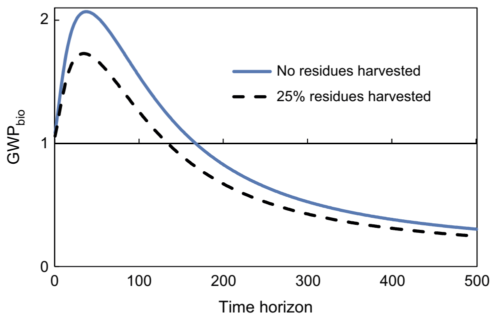

Fig. 3 GWP$_{bio}$ with and without collection of harvest residues for different time horizons.

166 years or less. If 25 percent of the residues are harvested, GWP$_{bio}$ exceeds 1.0 if the time horizon is 133 years or less.

As regards the lower GWP$_{bio}$ ratio when residues are harvested, it should be emphasized that the GWP$_{bio}$ factor is a relative (unit-based) measure of warming, see (15). In the case with residues included, more biomass is harvested and combusted, and this generates a larger CO_2 emission pulse at the time of harvesting. Recall that the emission pulse $E(\tau_h, \sigma)$ is increasing in σ. Hence, even though the *relative* warming potential of the harvest is lower in the case with residues than in the case where only the stems were harvested, the *absolute* potential warming impact is higher in the case in which harvest residues are collected. In the case where 25 percent of residues were harvested, the absolute warming potential, as defined in (13), was three percent higher than in the case where no residues were harvested.

Sensitivity analysis

The numerical model used in this paper relies on a number of uncertain factors. At the same time, different assumptions might be of significant importance (Lamers & Junginger, 2013). Forest growth after the age of maturity is probably most important. The accumulation of natural deadwood and the loss of soil carbon after harvesting are other uncertain parts of the model. A sensitivity analysis is therefore presented below. Here, it was assumed that the release of soil carbon to the atmosphere after harvesting and the accumulation of natural deadwood are reduced by 50 percent compared to the reference case. Moreover, it was assumed that, after the stand has reached the age of maturity, the growth of the living biomass is reduced by 50 percent compared to the reference case. Fig. 4 provides an overview of how the revised assumptions change the paths of the carbon pools. While Fig. 4a shows the harvest case, Fig. 4b shows the no-harvest case.

The results of the sensitivity analysis are shown in Table 3. In the case without any residues harvested, GWP$_{bio}$ is 1.13 with a time horizon of 100 years. If 25 percent of the residues are harvested, GWP$_{bio}$ drops to 0.94.

In addition to these sensitivity analyses, the sensitivity of the decomposition rate for dead organic matter (ω) has been checked. In the base case, $\omega = 0.04$. If this parameter was reduced to 0.02 or increased to 0.06, GWP$_{bio}$ changed to 1.60 and 1.49, respectively.

And, finally, it was checked how the harvesting age influences the results. If the harvesting age was reduced to 70 years, GWP$_{bio}$ was increased to 1.79. If the harvesting age was increased to a stand age of 200 years, GWP$_{bio}$ dropped to 1.38. Note that when the stand's age has reached 200 years, its carbon stock is almost in equilibrium.

Comparison of method and results in three other studies

As mentioned above, previous studies estimated the GWP$_{bio}$ ratio to be significantly lower than found in this study, see Table 4. Explanations for these differences are presented in the following, using the papers by Cherubini *et al.* (2011b), Guest *et al.* (2012), and Pingoud *et al.* (2011) as examples. It will be shown that results very close to the results in these three papers were achieved by placing appropriate restrictions on the model applied in this paper.

First, the paper by Cherubini *et al.* (2011b) is considered. Fig. 5 describes the basic structure of their model, which did not include any residues left on the forest floor or any pools of natural deadwood. Neither was soil carbon included in their model. In the harvest scenario, all biomass from the forest stand was removed at time $t = 0$ and immediately followed by an emission pulse corresponding to the release of all the carbon stored in the stand. This was followed by regrowth of the stand. With regard to regrowth, Cherubini *et al.* (2011b) assumed that it follows a typical stand's growth path until the biomass stock has reached the level it had at the time of harvesting. At that point in time, the stand growth is assumed to stop abruptly, as described in Fig. 5a. In the baseline (no-harvest) scenario, the forest stand's carbon stock is constant; see Fig. 5b. Hence, there is no growth and carbon capture in the no-harvest scenario.

Certain adjustments and simplifications of the model applied in this paper lead to a model very close to the model used by Cherubini *et al.* (2011b). With regard to the abrupt cessation of growth in the harvest scenario and the constant carbon stock in the no-harvest case,

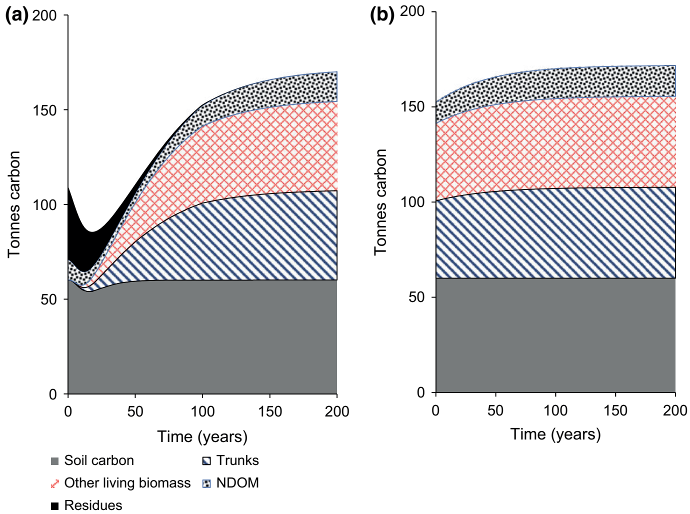

Fig. 4 Sensitivity analysis. Development of the carbon pools of a single stand, in a case with reduced growth in mature stands, reduced accumulation of natural deadwood and smaller effect of harvesting on soil carbon. (a) The harvest scenario. (b) The no-harvest scenario.

Table 3 Sensitivity analysis. Estimates of *GWP* ratios for 20, 100, and 500-year time horizons for fossil fuels and for wood fuels for different proportions of harvest residues. Case with reduced growth on mature stands, less accumulation of natural deadwood and less loss of soil carbon after harvesting

	TH = 20	TH = 100	TH = 500
No residues harvested	1.60	1.13	0.21
25% of residues harvested	1.40	0.94	0.17

this could be formulated as follows:

$$G^{*}(\tau,\tau_h) = \min(v_1(1-e^{-v_2\tau})^{v_3}, G(\tau_h)). \qquad (16)$$

where $G^{*}(\tau,\tau_h)$ now is the timber volume of a forest stand of one ha. The function $G(\tau)$ was defined in Eqn (1). Moreover, if it is assumed that $\theta = 1$, then harvesting would mean that all living biomass in the stand is removed at the time of harvesting. Assuming that $\beta = 0$ means that no dead organic matter is generated, while $s_1 = 0$ means that harvesting has no effects on soil carbon. Using these parameter values and the growth function described by (16), the GWP factor was estimated to be 0.44, which is very close to the result of 0.43 found by Cherubini *et al.* (2011b). Note that their estimates of GWP_{bio} for the 20 and 500-year time horizons were also reproduced; see the first two rows of results in Table 4.

Next, the study by Guest *et al.* (2012) is considered. In comparison with Cherubini *et al.* (2011b), an improved

Table 4 Estimates of GWP_{bio} for 20, 100, and 500-year time horizons when different restrictions are put on the model parameters, and the results of three corresponding studies

	TH = 20	TH = 100	TH = 500
$\beta = 0$, $\theta = 1$, $s_1 = 0$ and use of the function in expression (16)	0.96	0.43	0.08
Cherubini *et al.* (2011b)	0.97	0.44	0.08
$\beta = 0$, $\theta = 0.48$, $s_1 = 0$ and use of the function in expression (16)	1.16	0.58	0.10
Guest *et al.* (2012)	1.30	0.62	0.09
$\beta = 0$, $\theta = 1$, $s_1 = 0$ and use of the function in expression (1)	1.02	0.61	0.12
Pingoud *et al.* (2011)	1.00	0.60	na

approach was applied by Guest *et al.* (2012) as they took into account that stems constitute approximately half of the carbon stock of a typical forest stand. It follows that harvest residues then become an issue. Moreover, they considered different scenarios for the extraction of harvest residues. Fig. 6a illustrates their model in the case where all residues were left on the forest floor. In that case, there is an emission pulse at time $t = 0$ corresponding to the amount of carbon contained in the stock of stems in the stand at the time of harvesting. However, we again observe that, at the point in time

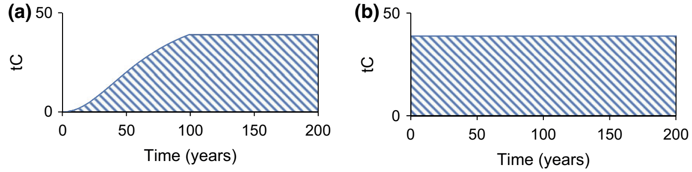

Fig. 5 Illustration of the development of carbon stored in the considered forest stand as modeled by Cherubini *et al.* (2011b). (a) The harvest scenario. (b) The no-harvest scenario.

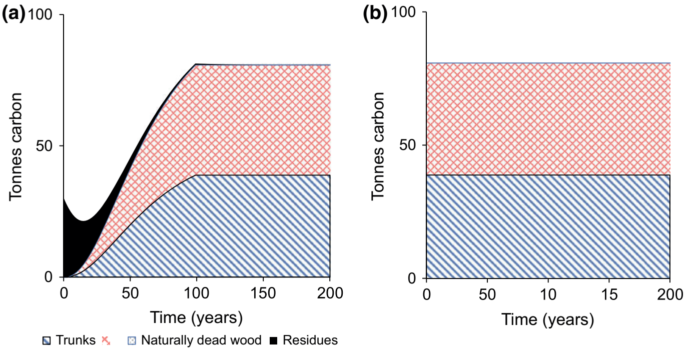

Fig. 6 Illustration of the development of carbon stored in the considered forest stand as modeled by Guest *et al.* (2012). (a) The harvest scenario. (b) The no-harvest scenario.

when the biomass of the stand has reached the level it had at the time of harvesting, forest growth stops abruptly, see Fig. 6a. Note that Fig. 6b shows their baseline (no- harvest) scenario. In that case, the stand's biomass is fixed.

It follows that the model applied in this paper becomes similar to the model applied by Guest *et al.* (2012) if $\beta = 0$ (no naturally dead organic matter is generated) and $s_1 = 0$ (the harvest has no effects on the stock of soil carbon). And, finally, the function described by (16) should be applied instead of (1). With these simplifications of the model, the GWP_{bio} ratio was found to be 0.58, relatively close to the ratio of 0.62 found by Guest *et al.* (2012); see the third and fourth rows of results in Table 4.

Finally, Pingoud *et al.* (2011) should be considered. Fig. 7 describes the basic structure of their model, which is similar to the model applied by Cherubini *et al.* (2011b). They did not include any residues left on the forest floor or any pools of natural deadwood. Neither was soil carbon included in their model. In the harvest scenario, all biomass from the forest stand was removed at time $t = 0$, and this was immediately followed by an emission pulse corresponding to the release of all the carbon stored in the stand. With regard to regrowth, however, Pingoud *et al.* (2011) did not assume an abrupt stop at the time of maturity, and a baseline with continued growth was adopted.

It follows that the model applied in this paper becomes similar to the model applied by Pingoud *et al.* (2011) if it is assumed that $\theta = 1$ (harvesting would then mean that all living biomass on the stand is removed at the time of harvesting), $\beta = 0$ (no naturally dead organic matter is generated) and $s_1 = 0$ (the harvest has no effects on the stock of soil carbon). With these adjustments of the model, the GWP_{bio} ratio was found to be 0.61, relatively close to the ratio of 0.60 found by Pingoud *et al.* (2011); see the two last rows in Table 4.

The calculations in this section give an indication of the importance of the different assumptions. Some readers might be looking for a more precise quantification of how large a proportion each of the different assumptions contributed to the deviation in results. However, such an exercise might yield limited value added because the *interactions* between the different assumptions are of crucial importance. Nevertheless, it is clear that the inclusion of harvest residues in the calculations is the most important factor. The inclusion of soil carbon, on the other hand, is of minor importance.

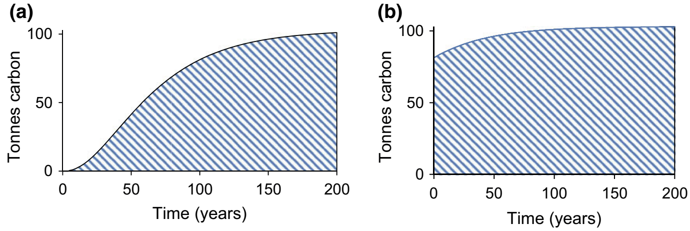

Fig. 7 Illustration of the development of carbon stored in the considered forest stand as modeled by Pingoud *et al.* (2011). (a) The harvest scenario. (b) The no-harvest scenario.

However, as emphasized, the release of soil carbon after harvesting is not well understood and might be larger than assumed in this paper.

Discussion

Some comments are warranted on the limitations of the scope of this study. The purpose is not to paint a complete picture of all the environmental pros and cons of wood fuels. For example, this paper only considered CO_2. It is left to future studies to include the non-CO_2 climate-forcing effects of forestry, for example albedo, the effects of aerosols, etc. (Spracklen *et al.*, 2008; Bright *et al.*, 2012). Moreover, the combustion of both fossil fuels and wood fuels generates, to varying degrees, different substances harmful to health as well as greenhouse gases other than CO_2. For example, the combustion of wood fuels in open fireplaces and stoves leads to the release of substantial amounts of methane (CH_4); see Haakonsen & Kvingedal (2001) and the IPCC-guidelines for energy, Eggleston *et al.* (2006). The harmful emissions from wood burning in open fireplaces and stoves are substantial (Haakonsen & Kvingedal, 2001).

It should also be emphasized that the estimated effects of the harvesting and combustion of forest biomass can only be directly applied by decision makers if the harvest from the studied stand is used for bioenergy purposes. The aggregated approach applied does not consider cases in which different forest biomass components originating from harvests are used for other purposes. In conventional forest management, a significant proportion of stemwood from final felling is often used, for example, in construction materials, fiber-products, etc., while only some of the stems are used for energy purposes together with the harvested residues. This supports an approach that identifies the differences in the climate impacts of energy use of specific fractions of the harvest (Repo *et al.*, 2012).

It should also be noted that the approach taken in the present paper results in a description of the climate impacts of current, unchanged forestry practice. The study does not describe the climate impacts of a change in forest management from, e.g., increased harvest levels to meet increased bioenergy targets (described in, e.g., Holtsmark, 2012) or the climate impacts of specific forest biomass fractions, e.g., stems, branches or stumps (as in, e.g., Repo *et al.*, 2011, 2012).

Moreover, it should be noted that knowledge is limited about the extent to which the harvesting of residues will trigger an increased release of soil carbon after the harvest. That is not accounted for in the present calculations. Hence, the estimated GWP_{bio} factors when the harvesting of residues was included might be too optimistic; see the discussion in Repo *et al.* (2011). Moreover, the collection of forest residues might not just have an impact on soil carbon, but also influence forest growth as well (Helmisaari *et al.*, 2011; Lamers *et al.*, 2013).

With regard to the numerical model applied in this paper, there is a considerable potential for improvement. A simple geometric model for the decomposition of forest residues was applied. Although sensitivity analyses (not presented here) show that the results are relatively insensitive to the speed and profile of the decomposition rate, improvements on this point could easily be implemented, for example, based on the Yasso model (Tuomi *et al.*, 2009, 2011). Moreover, along the same lines, the time profiles for the accumulation of natural deadwood and more general accumulation of dead and living biomass in old forests should be studied further (Carey *et al.*, 2001; Luyssaert *et al.*, 2008). Helin *et al.* (2012) emphasized that the development of the carbon stock of mature forests is uncertain and that different scenarios in that respect are important. The sensitivity analysis presented points in the same direction. This study is also limited to an analysis of a forest stand that was harvested at a stand age of 100 years. An interesting extension would be to consider stands that grow both faster and slower along with different harvesting ages, as observed in Cherubini *et al.* (2011a,b).

Despite these limitations, the study still presents an improved method for estimating GWP_{bio}. The proposed method includes modeling the dynamics of the forests' multiple carbon pools, how these pools are impacted by harvesting, and comparing the harvest scenario with a realistic baseline without harvesting. Based on the proposed method, the paper re-estimated the GWP_{bio} ratio. The numerical examples demonstrate that the proposed method results in estimates of GWP_{bio} that are two to three times as high as the estimates of GWP_{bio} found in earlier studies. While earlier studies estimated GWP_{bio} to be significantly below 1, this study estimated GWP_{bio} to be significantly above 1 when a slow-growing forest stand was considered.

An important question is how the estimates of the GWP_{bio} ratio should be interpreted. For example, Cherubini *et al.* (2011b) found GWP_{bio} estimates significantly below 1 when a 100-year time horizon was applied, and they concluded on that basis that 'bioenergy becomes an attractive climate mitigation option […] which cools the climate when particular forest management practices are applied' (Cherubini *et al.*, 2011b, p 65). It should be noted here that any positive GWP values smaller than 1 signify that the climate impact of a mass unit of the greenhouse gas considered is lower than the warming impact of a mass unit of fossil CO_2, but it still warms the climate. Only negative GWP values mean that the emissions considered cool the climate in absolute terms. Thus, the conclusions in the quoted text are potentially misleading for the reader.

The results of this paper provide a basis for the following conclusions. First, the climate impact of the harvesting and combustion of slow-growing forest biomass seems to be higher than previous assessments have concluded. Second, the climate impact per unit of CO_2 emitted seems to be even higher for the combustion of slow-growing biomass than for the combustion of fossil carbon in a 100-year time frame.

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Essay 6
A comparison of the global warming effects of wood fuels and fossil fuels taking albedo into account

Sligthly revised version of paper published in *GCB Bioenergy*

A comparison of the global warming effects of wood fuels and fossil fuels*

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Abstract

Traditionally wood fuels, as other bioenergy sources, have been considered carbon neutral because the amount of CO_2 released could be offset by CO_2 sequestration due to the regrowth of the biomass. Thus, until recently most studies assigned a global warming potential (GWP) of zero to CO_2 generated by combustion of biomass (biogenic CO_2). Moreover, emissions of biogenic CO_2 are usually not included in carbon tax and emissions trading schemes. However, there is now increasing awareness of the inadequacy of this treatment of bioenergy, especially bioenergy from boreal forests. Recently, Holtsmark (2015) quantified the GWP of biogenic CO_2 from slow-growing forests (GWP_{bio}) to be significantly higher than the GWP of fossil CO_2, when a 100-year time horizon was applied. Hence, the climate impact seems to be even higher for the combustion of slow-growing biomass than for the combustion of fossil carbon in a 100-year time frame. The present study extends the analysis of Holtsmark (2015) in three ways. First, it includes the cooling effects of increased surface reflectivity after harvest (albedo). Second, it includes a comparison with the potential warming impact of fossil fuels taking the CO_2 emissions per unit of energy produced into account. Third, the study makes a link between the literature estimating GWP_{bio} and the literature dealing with the carbon debt, as model simulations estimating the payback time of the carbon debt is presented. The conclusion is that also after these extensions of the analysis, bioenergy from slow growing forests usually has a larger climate impact in a 100 years time frame than fossil oil and gas. Whether bioenergy performs better or worse than coal depends on a number of conditions.

Keywords: Bioenergy, boreal forests, climate change, carbon, albedo, fossil fuels.

1 Introduction

Traditionally, bioenergy has been considered to be carbon neutral because the released carbon is absorbed by the harvested crops' regrowth. Thus, CO_2 released from the combustion of bioenergy has until recently been given a global warming potential (GWP) of zero in most LCA analyses, see for example Bright and Strømman (2009) and Sjølie et al. (2010). For the same reason, no country imposes taxes on CO_2 emissions from the combustion of bioenergy, and firms included in the European Union emissions trading market are not committed to acquiring and surrendering allowances for CO_2 emissions from the combustion of bioenergy.

There is now far-reaching agreement that biofuels from forests should not be considered to be carbon neutral; see for example Chum et al. (2011), Friedland and Gillingham (2010),

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Haberl (2013), Haberl et al. (2012), Haberl et al. (2013), Holtsmark (2012), Hudiburg et al. (2011), Schulze et al. (2012), Searchinger et al. (2009), McDermott, Howarth, and Lutz (2015). One argument is that there is a time lag between the harvest and the full regrowth of the forest. In addition comes that harvesting influences the dynamics of the harvested stands' carbon pools. For example, after harvesting there will often be a net release of carbon from the soil layer. More important, however, is that if the forest is not harvested there will usually be further growth and accumulation of both dead and living biomass on the stand. Thus, to estimate the potential climatic effects of harvesting, the harvest scenario must be compared to a no-harvest scenario that includes a description of the stand's carbon dynamics in that case, see Helin et al. (2013), Holtsmark (2013b), Holtsmark (2013a), Olsson et al. (1996).

If bioenergy should no longer be considered carbon neutral, the question is how to quantify its climate impact, for example in LCA analysis, or in other evaluations of the climatic properties of bioenergy. One possibility is to use the well-known concept GWP. This concept is a frequently used metric when the climate impacts of greenhouse gases (GHGs) need to be compared. GWP quantifies the cumulative potential warming effect of a pulse of GHGs over a specified time frame, taking its absorption of infrared radiation and atmospheric lifetime into account. GWP is a relative measure and the GWP of CO_2 is given the ratio 1.

Clearly, CO_2 released by combustion of biomass has exact the same climatic impacts as CO_2 released by combustion of fossil fuels. However, it could be argued that CO_2 released from combustion of biomass has a different *net* climatic effect when it is taken into account that harvesting of the biomass influences the future time profile of the carbon uptake from the harvested stand. For example, when taking regrowth into account, Cherubini et al. (2011a) found GWP_{bio} to be 0.43 when they considered a stand of a slow-growing forest that was harvested at an age of 100 years. Later Cherubini, Strømman, and Hertwich (2011), Cherubini, Bright, and Strømman (2012), Bright, Cherubini, and Strømman (2012), Guest et al. (2013), and Pingoud, Ekholm, and Savolainen (2012) presented estimates of GWP_{bio} in the interval 0.34 - 0.62 when slow-growing forest stands were considered. The fact that these estimates are significantly below 1.0 indicates that bioenergy from slow-growing forests from a climate perspective is better than fossil fuels.

However, Holtsmark (2015) found that the abovementioned contributions had some methodological weaknesses. Cherubini, Strømman, and Hertwich (2011), Cherubini, Bright, and Strømman (2012), Bright, Cherubini, and Strømman (2012), and Pingoud, Ekholm, and Savolainen (2012) applied models of a forest stand that did not include effects of harvesting on the dynamics of important carbon pools such as residues, natural deadwood, and carbon.

Moreover, only Pingoud, Ekholm, and Savolainen (2012) included a realistic baseline scenario. The other studies made the simplifying assumption that, if not harvested, there is no further growth and accumulation of carbon in a mature stand. Guest et al. (2013) did include harvest residues in their analysis, but they did not include natural deadwood or effects on soil carbon, and they did not construct a realistic baseline scenario. The importance of including these features is emphasized in a number of studies, for example Asante, Armstrong, and Adamowicz (2011), Asante and Armstrong (2012), Buchholz et al. (2014), Fontaine et al. (2007), Holtsmark, Hoel, and Holtsmark (2013), de Wit and Kvindesland (1999), Kjønaas et al. (2000), Johnson and Curtis (2001), Kaneyuki and Lee (1995). Moreover, Cherubini, Strømman, and Hertwich (2011), Cherubini, Bright, and Strømman (2012), Bright, Cherubini, and Strømman (2012), Guest et al. (2013) made the assumption that in the harvest scenario there is a sudden stop in the growth of biomass on the stand when the stand's age in becomes equal to the stand's age at time of harvest in the previous rotation, see Figure 1, which shows a case where the rotation length is 90 years.

Holtsmark (2015) presented an improved method for estimating the net warming impact of biofuels. Firstly, Holtsmark (2015) compared the harvest scenario with a no-harvest baseline scenario that took into account that accumulation of dead and living biomass usually will continue if the stand is not harvested. Secondly, the model introduced included the dynamics of the forest stand's main carbon pools, including harvest residues, the pool of natural deadwood as well as all parts of growing trees such as branches, tops, stumps and roots in addition to the stems. The effects of harvesting on the pool of soil carbon were modeled as well. Figure 2 illustrates the model setup in Holtsmark (2015).

The simulation results presented in Holtsmark (2015) demonstrated clearly the importance of including all the forest stand's carbon pools in the model as well as a realistic reference scenario. When a 100-year time horizon was applied to a forest stand of age 100 years, the resulting GWP_{bio} estimate was found to be 1.5, i.e., more than three times as high as the estimates of GWP_{bio} found in Cherubini et al. (2011) and Cherubini, Strømman, and Hertwich (2011).

The contribution of the present paper is three-fold. First, it improves the method of Holtsmark (2015) by taking a possible cooling effect of reduced albedo after harvest into account, cf. Bright, Cherubini, and Strømman (2012), Cherubini, Bright, and Strømman (2012) and Lutz and Howarth (2014). Second, the net warming impact of wood fuels is compared to the net warming impact of coal, oil and gas, when considering the fuels' respective warming impacts per unit energy produced. Third, the single harvest approach taken in the above mentioned studies on GWP_{bio} is supplemented with simulations taking the landscape approach in order to show the time profile of how increased use of bioenergy from slow-growing forest on a permanent basis, will cause global warming. This extension of the analysis makes a link from the literature on GWP_{bio} to the literature estimating the payback time of the biofuel carbon debt (Bernier and Paré (2013), McKechnie, Colombo, and MacLean (2014), Holtsmark (2012)).

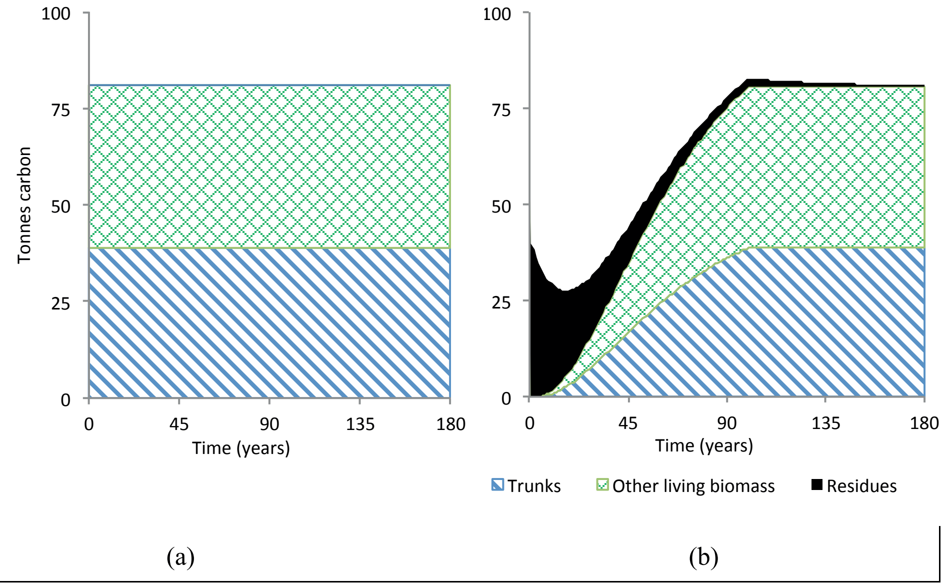

Figure 1 Illustration of the development of carbon stored in the considered forest stand as modeled by Guest et al. (2013). (a) The no-harvest scenario (b) The harvest scenario.

The outline of the paper is as follows. The next section briefly presents the model of the considered forest stand as well as the model for the accumulation of carbon in the atmosphere. As exactly the same method was applied in Holtsmark (2015), readers looking for details about how the dynamics of the forest stand was modeled, are directed to that paper. The next section also introduces the model for albedo before the proposed method for calculating GWP_{bio} is presented. The third section presents the results. Finally, there is a section discussing the results and concluding.

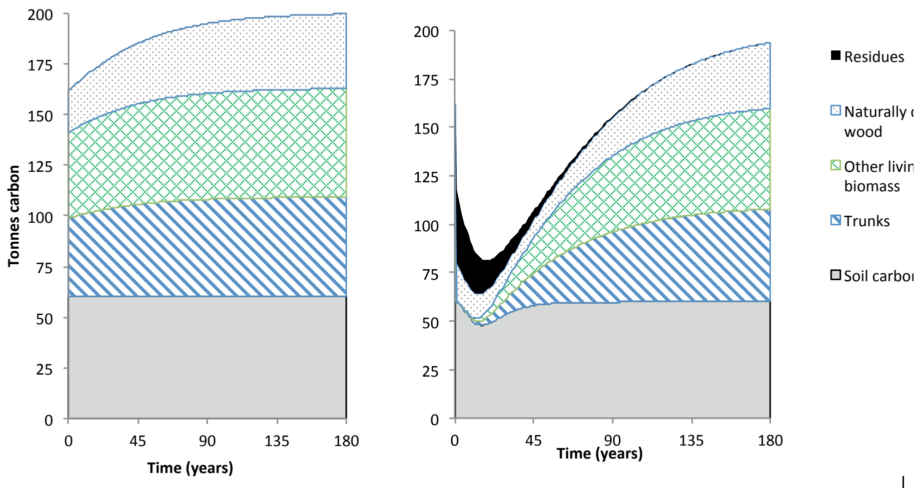

Figure 2 Illustration of the development of carbon stored in the considered forest stand as modeled in the present article. (a) The no-harvest scenario (b) The harvest scenario.

2 Materials and methods

2.1 The model of a forest stand

The basis for the estimation of GWP_{bio} is a comparison of the time profile of the forest stand's total carbon stock in the no-harvest scenario (Figure 2a) and in the harvest scenario (Figure 2b) and the corresponding net fluxes of CO_2 between the stand and the atmosphere in both scenarios. The growth function for the stand was calibrated to fit into the standard production tables for Norway spruce of medium productivity given in (Braastad 1975). The volume of trunks of is 194 m^3/ha when the stand age is 100 years. This is in agreement with results of simulations with the Norwegian forest model AVVIRK-2000 (Eid and Hobbelstad 2000), which indicate that scaling up the harvest in Norway would give on average approximately 194 m^3/ha. As a starting point, it was assumed that the stand's age at time of harvest ($t = 0$) is 100 years, with a total carbon stock of 162 tC (before harvesting). In the harvest scenario, all stems of living trees are removed from the stand at time $t = 0$ with subsequent combustion giving rise to a pulse of CO_2 corresponding to the amount of carbon contained in the stems (39 tC). Hence, after harvesting, the stand stores 123 tC; see Figure 2b. A case including the use of harvest residues was also considered, giving rise to a correspondingly higher emission pulse at time $t =$

0 and correspondingly smaller subsequent emissions from the decomposition of residues (Repo et al. 2012, Repo, Tuomi, and Liski 2011). Note, however, that the numerical results might draw a too optimistic picture of the use of residues for energy purposes, as it was assumed that removal of residues does not influence future growth or the release of soil carbon (Helmisaari et al. 2011, Palosuo, Wihersaari, and Liski 2001).

After harvesting, new trees start growing; see the hatched and cross-hatched areas in Figure 2b. Residues left on the forest floor decompose; see the black area. Moreover, natural deadwood (NDOM) that was present in the stand at the time of harvesting also gradually decomposes, while new naturally dead biomass is generated; see the dotted area in Figure 2b.

With regard to the dynamics of the soil carbon pool, it was assumed that harvesting results in some years with a net release of carbon from the soil. Thereafter, the soil carbon pool gradually returns to its original state; see Figure 2b. The development of the stand's carbon stock in the no harvest baseline scenario is shown in Figure 2a. The starting point is that the stand's age is 100 years at $t = 0$. Hence, at time $t = 0$ in the no-harvest scenario, the sizes of the carbon pools are the same as at time $t = 100$ in the harvest scenario, cf. Figure 2a and b. Moreover, in the no-harvest scenario, there is continued forest growth after $t = 0$ with a corresponding continued accumulation of natural deadwood. In the no-harvest scenario, the soil's carbon pool is assumed to be constant over time.

There is significant uncertainty about the likely development of the carbon stock of an old stand. However, in accordance with, e.g., Luyssaert et al. (2008) and Carey et al. (2001), I assumed continued accumulation of carbon even in old stands. As this is an uncertain part of the scenario, Holtsmark (2015) provided a sensitivity analysis with a significantly smaller accumulation of carbon in older stands.

2.2 Accumulation of carbon in the atmosphere and radiative forcing effects

The model for the lifetime of carbon in the atmosphere is the same model as applied in Holtsmark (2015) as well as Cherubini et al. (2011), see those papers for details. The carbon lifetime model is based on Joos and Bruno (1996), Joos et al. (1996), Joos et al. (2001) labeled the Bern 2.5CC carbon cycle model. It takes into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere as well as the sea. The profile of the broken double-lined curve in Figure 3 depicts the remaining proportion at time t of a CO_2 pulse generated at time $t = 0$ from combustion of an amount of fossil fuels (oil) in the no-harvest scenario. The Bern 2.5CC model is also applied to the pulse emission caused by combustion of the harvest as well as the flux from atmosphere to the forest generated by the stand's growth, as well as the fluxes of CO_2 caused by decomposition of natural deadwood and harvest residues left on the forest floor; see further details in Holtsmark (2015).

To make the potential warming effect of CO_2-emissions comparable to the cooling effect of increased albedo, the additional radiative forcing of additional carbon in the atmosphere, here labeled $\Delta RF(t)$, has to be modeled. Additional RF from an additional amount $\Delta A(t)$ of carbon is assumed to be

$$\Delta RF(t) = 5.35 \cdot \ln(1+\Delta A(t)/A_0(t)) \text{ W/m}^2, \quad (1)$$

where $A_0(t)$ is the amount of carbon in the atmosphere in absence of the considered pulse and z is a parameter.

First, note that it follows from (1) that the amount of additional RF form a certain carbon pulse is sensitive to the concentration of CO_2 in the atmosphere. As the atmospheric concentration is increasing, additional RF from additional CO_2 is decreasing. However, Caldeira and Kasting (1993) found that as the lifetime of CO_2 in the atmosphere is likely to be increasing as the atmospheric concentration is increasing, it is a sound approximation to fix the background CO_2 concentration at the current level in this type of analysis. This was therefore done, see equation (2). Given that the surface of the planet is approximately $5.10072 \cdot 10^{14}$ m², the additional RF of an additional amount of carbon is

$$\Delta RF(t) = 5.10072 \cdot 10^{14} \cdot z \cdot \ln(1+\Delta A(t)/A_{2013}) \text{ W}, \quad (2)$$

where A_{2013} is the current amount of carbon in the atmosphere, set to 855 GtC.

Figure 3 illustrates how the combination of the model works. As already mentioned, the broken double-lined curve in Figure 3 depicts the remaining proportion at time t of a CO_2 pulse generated at time $t = 0$ from combustion of an amount of fossil fuels (oil) in the no-harvest scenario. The left axis shows the effect on RF in kW while the right axis gives the corresponding amount of carbon in tC. The unbroken, grey curve shows the net effect of the pulse emission caused by combustion of the harvest together with the effect of the release of carbon due to decomposition of dead organic matter left on the stand after harvest as well as the stand's carbon capture due to regrowth after harvest.

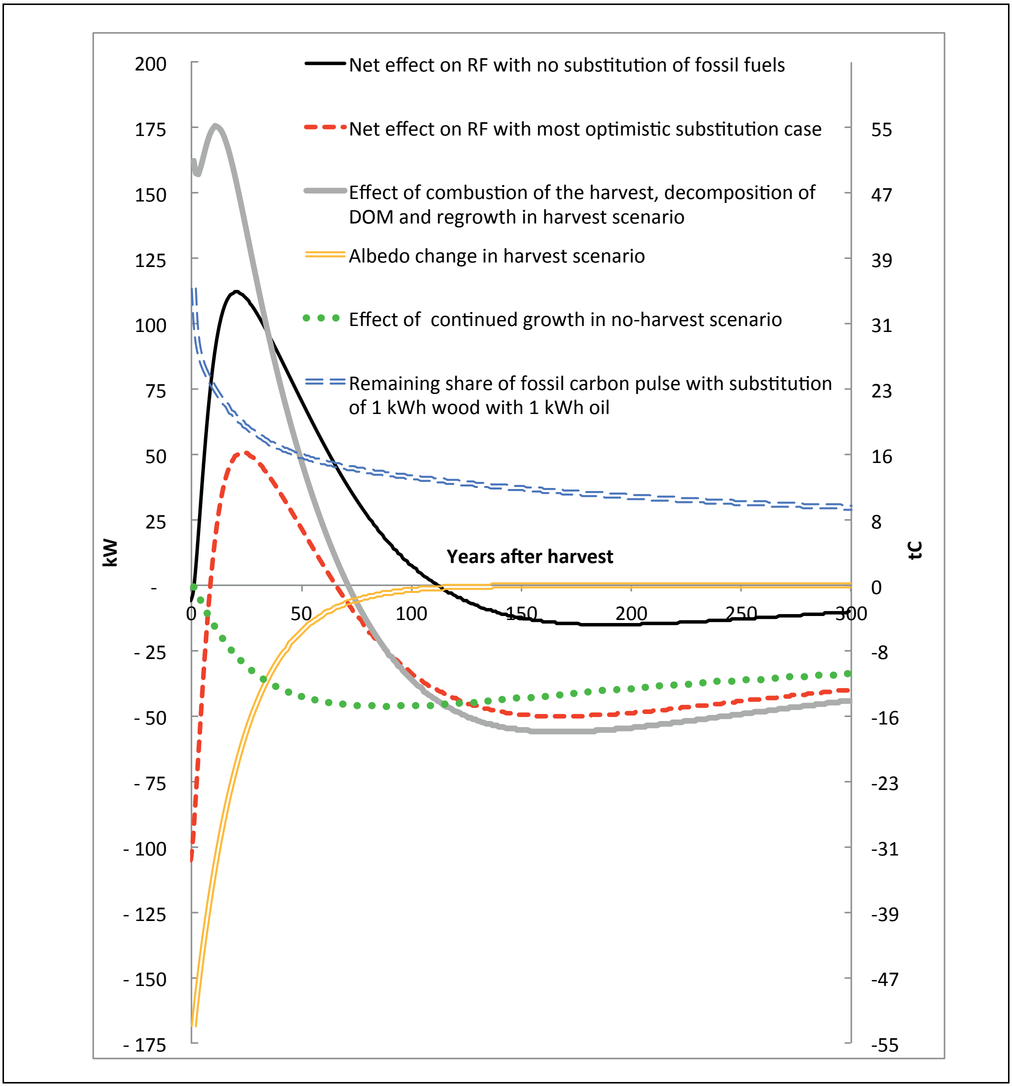

Figure 3 Illustration of the development of the effects of harvest and no-harvest on the amount of carbon in the atmosphere (also measured in radiative forcing on the left axis).

Next, consider the albedo effect. It was assumed that clear-cutting of a considered stand of 1 ha gives an immediate rise in albedo labeled. This was labeled $\Delta RF_{albedo}(0)$ using kW as the unit. The albedo effect is gradually reduced as regrowth takes place. Hence, the albedo *t* years after harvest was assumed to be

$$\Delta RF_{albedo}(t) = (1-\delta_{\text{albedo}}) \cdot \Delta RF_{albedo}(0). \qquad (3)$$

In practice, the albedo effect from clear-cutting a site varies significantly depending on the exact site considered. The parameters in (3) are based on Cherubini, Bright, and Strømman (2012), more specifically their Norwegian cases. The parameter δ_{albedo} was set to 0.045, and $\Delta RF_{albedo}(0)$ to 135.1 kW/ha and 168.6 kW/ha in the cases without and with extraction of aboveground residues from the stand, respectively. These two cases are different as Cherubini, Bright, and Strømman (2012) found that the reflection is larger from a stand if the residues are removed from the stand, compared to the case where residues are left on the forest floor. The time profile of the albedo-effect of harvesting, in the case where also residues were harvested, is shown with the double-lined unbroken curve in Figure 3.

2.3 Calculation of energy output and CO_2 emissions from combustion of wood and fossil fuels

As mentioned, harvesting at stand age 100 years was assumed to provide 194 m^3 wood when only the trunks were harvested. In addition, a case was considered where approximately 75 percent of tops and branches were harvested together with the stems. These harvest residues are assumed to constitute 53 m^3. Hence, a total of 247 m^3 of wood are harvested in that case. As 1 m^3 of wood is assumed to contain 200 kg C, this means that combustion of the harvest releases 38.8 tC and 49.3 tC and the case without and with collection of residues, respectively.

3 Results

3.1 Estimates of GWP_{bio}

Table 1 provides the estimates of GWP_{bio}. Two cases are displayed, one with no collection of harvest residues and one with collection of 34 percent of the residues. A proportion of 34 percent of the residues was chosen because that could represent a case where all branches and tops were harvested together with the trunks.

Within both the two cases displayed in Table 1, the first line shows the estimates of GWP_{bio} before taking albedo-effects into account. Hence, these numbers correspond to the GWP_{bio}-estimates presented in Holtsmark (2015). Because an improved model for decomposition of dead organic matter was applied in the present study, the estimates are slightly different from the estimates presented in Holtsmark (2015).

The second lines of the two cases displayed in Table 1, show the albedo effect. This is negative because harvesting increases the reflectivity from the stand and cools the climate. Note that there is a slight difference between the albedo effect in the cases with and without collection of residues. As mentioned, I adopted the assumptions made by Cherubini, Bright, and Strømman (2012), that collection of residues increases the reflectivity from the forest ground. However, at the same time residue collection increases the emission pulse from combustion of the harvest. Here it is important to have in mind that GWP_{bio} is a relative (unit-based) measure of warming. In the case with residues harvested the absolute warming effect of the emission pulse caused by combustion is larger than in the case without residue collection. Hence, although the absolute albedo effect is larger in the case with collection of residues, the relative albedo effect (relative to the amount of biomass harvested) is smaller.

Table 1. GWP_{bio} for the cases with and without collection of residues.

Time horizon	20	100	500
Case with no collection of residues			
Bio CO_2	1.92	1.59	0.32
Albedo	-1.01	-0.49	-0.15
Net effect	0.91	1.10	0.16
Case with collection of residues			
Bio CO_2	1.54	1.20	0.24
Albedo	-0.93	-0.45	-0.14
Net effect	0.62	0.75	0.10

Row three of the two cases displayed in Table 1 shows the net effect when the cooling effect of increased albedo is subtracted from the warming effect of CO_2. In the case without subsidies, the GWP_{bio} is slightly higher than 1 with a time horizon of 100 years, while it is below 1 in the case with residues collection.

If a time perspective of 500 years is found to be more relevant than 100 years discussed above, the results become significantly more in favor of wood fuels. For example, in the case with no residues harvested, and with a 500-year time horizon, GWP_{bio} was found to be 0.10 and 0.16 in the case with and without collection of residues; see Table 1.

As mentioned in the introduction, the results presented here and in (Holtsmark 2015) are different from results presented in earlier studies. For example, Table 1 in Cherubini, Bright, and Strømman (2012) displays net GWP_{bio} factors of 0.20 and 0.12, in very similar cases, when a 100 year time horizon was applied. However, as discussed in further detail in Holtsmark (2015), Cherubini, Bright, and Strømman (2012) applied a model of a forest stand of the type used in Guest, Cherubini, and Strømman (2013), see Figure 1. It would therefore be valuable to check how the model performs if it is changed in accordance with the model design applied by Cherubini, Bright, and Strømman (2012). That would mean that an abrupt stop in the forest growth when the stand age becomes 100 years has to be assumed. Moreover, in the no-harvest reference scenario the forest stand's carbon stock should be kept fixed. And finally, it has to be assumed no accumulation of dead organic matter and no release of carbon from the soil after harvesting.

Table 2 here shows the simulation results if the model of the forest stand applied in this paper was changed in these ways. The albedo effects were not changed compared to Table 1. However, the CO_2-effects become smaller, with a picture more in the favor of bioenergy, as in Cherubini, Bright, and Strømman (2012). This illustrates the importance of using a model of a forest stand that includes the dynamics of all the main carbon pools as well as using a realistic no-harvest reference scenario when climatic effects of bioenergy is to be assessed.

Table 2. GWPs for the cases with and without collection of residues, when the model of the forest stand was simplified along the lines applied by Cherubini, Bright, and Strømman (2012)

Time horizon	20	100	500
Case with no collection of residues			
Bio CO_2	1.25	0.65	0.11
Albedo	-1.01	-0.49	-0.15
Net effect	0.23	0.15	-0.04
Case with collection of residues			
Bio CO_2	1.11	0.55	0.09
Albedo	-1.00	-0.49	-0.15
Net effect	0.12	0.06	-0.06

3.2 Comparison with fossil fuels

The numbers in Table 1 show the net warming effect of CO_2-emissions from combustion of biomass, when it is taken into account how harvesting changes the dynamics of the different carbon pools of the considered forest stand as well as the lifetime of CO_2 in the atmosphere. However, for a complete assessment of bioenergy compared to fossil fuels, it should also be taken into account how much CO_2 is emitted per kWh that is produced. Such a comparison is reported in the following.

The energy generated by combustion of wood depends on the moisture content, which here was assumed to be 15 percent. With 100 percent efficiency, combustion of wood will then give approximately 2050 kWh/m^3, see Hohle (2001). With an estimated carbon content of 200 kg C/m^3, the emission ratio will be 358 g CO_2/kWh with 100 percent combustion efficiency. In comparison, and as a benchmark, it was assumed average emissions of 356 g CO_2/kWh for coal, 255 g CO_2/kWh for oil and 186 g CO_2/kWh for gas when there is 100 percent efficient combustion.

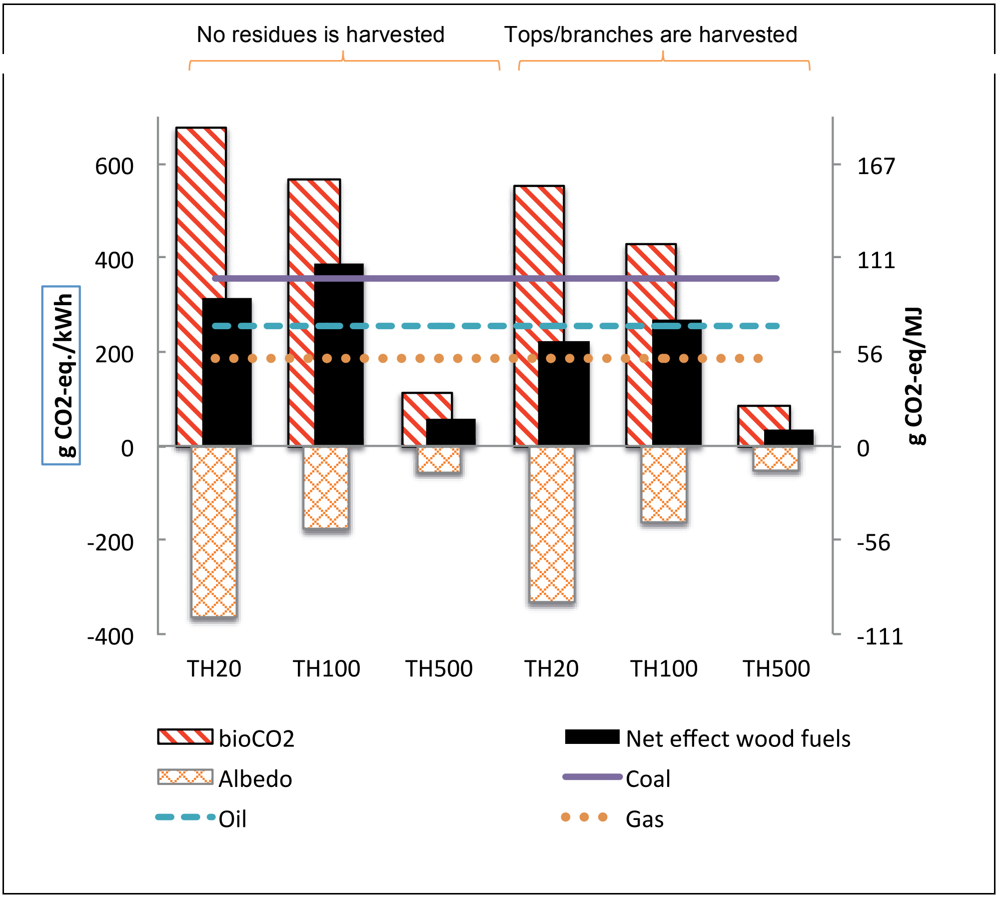

Figure 4. The global warming potentials of woodfuels in g CO_2-equivalents per kWh, with the warming potentials of fossil fuels included as benchmarks. Both with regard to biofuels and fossil fuels, there is assumed 100 percent combustion efficiency. The hatched columns show the net warming effect of harvest due to its influence on the carbon cycle. The cross-hatched columns show the albedo effect of harvesting, while the black columns show the net effect on warming when both albedo and effects on the carbon cycle is taken into account.

In practice there will never be 100 percent efficient combustion. For example, a power plant typically has a combustion efficiency of around 40 percent when the energy source is coal or wood pellets, giving approximately 900 g CO_2/kWh in both the wood and coal case. On the other hand, an efficient modern gas power plant is more likely to have combustion efficiency as high as 55 percent, giving approximately 340 g CO_2/kWh. In other words, there are large variations with regard to combustion efficiency depending on the exact technology applied.

Nevertheless, as a starting point for comparison 100 percent efficiency was used to all fuels. If the results should be applied to certain technologies where the efficiency ratios are different for combustion of biomass compared to fossil fuels, the emission ratios should be adjusted accordingly. Hence, the results presented here is a starting point for such comparisons.

There are also large variations with regard to the energy losses and energy consumption in relation to both harvesting and processing of wood fuels as well as production, refining and distribution of fossil fuels. The energy losses with regard to the production of liquid biofuels from wood are especially large. Nevertheless, to make the analysis as simple and transparent as possible, emissions related to harvesting and processing are not included in the calculations presented in this paper. This applies also when we consider fossil fuels. Again the results here serve as a transparent starting point for comparison. With information about energy losses related to the degree of combustion efficiency and energy use related to processing etc, the results reported here could be supplemented to provide more specific policy advices related to different technologies.

Figure 4 shows the global warming effect of woodfuels in g CO_2-equivalents per kWh, with the warming impacts of fossil fuels included as benchmarks. The three left groups of columns represent the case *without* collection of any residues, while the three right groups of columns represent the case *with* collection of 75 percent of tops and branches in addition to the stems. Three different time horizons were considered; 20 years, 100 years and 500 years.

3.3 From a single harvest approach to a permanent harvesting approach

The previous sections reported results from simulations of harvesting of a single stand at time t=0. However, the starting point for the discussion of the climatic consequences of use of bioenergy, is whether the society, *on a long term basis,* should increase the use of bioenergy. That would mean harvesting not only in year t=0, but in the subsequent years as well. To analyze that type of policy scenario, a "landscape approach" should be taken. More specifically, a forest consisting of 100 stands is considered. Each stand in this forest has exactly the same properties as the stand that was analyzed in the previous sections, see Figure 2. However, it is in the following assumed that the stands' ages (years since last harvest) vary in the following way. The age of stand number 1 is 100 years in year t=0 and ready for harvest. The age of stand number 2 is 99 years at time t=0, and will thus be ready for harvest in year t=1, and so forth. Hence, in year t=99 the last stand is ready for harvest, and in year t=100 stand number 1 is again mature and ready for harvest, and a new rotation follows.

Before the landscape approach is analyzed, we need to return to the single harvest approach and Figure 3. This diagram describes the consequences of harvesting stand number 1 in year *t*=0. First, consider the single-lined black curve in Figure 3. This shows the time profile of the net effect of harvest on RF if increased supply of bioenergy does not lead to any reductions in the consumption of fossil fuels. This is a limiting case . It is more likely that increased supply of bioenergy will lead to lower energy prices, which in turn will lead to reduced supply, and thus also reduced consumption of fossil fuels (Hutchinson, Kennedy, and Martinez 2010). Exactly what types of energy consumption that will be reduced when bioenergy supply is increased and to what extent, depends on a large number of conditions that are beyond the limits of this article. To analyze that question, a general equilibrium model would be an appropriate tool. However, even then we would have been left with large degrees of uncertainty. Therefore, this article seeks to incorporate the significant uncertainty at this point by considering a number of limiting cases. The real consequences of increased supply of bioenergy are then most likely somewhere in between these limiting cases.

First, it is assumed that 1 kWh of wood fuels replaces 1 kWh oil, and the combustion efficiency is assumed to be the same for wood and oil. The second and third cases provide the corresponding exercises with regard to replacement of gas and coal, respectively.

The right diagram in Figure 5 shows two curves redrawn from Figure 3. The broken curve shows the net effect on RF of harvesting stand 1 in year t=0, when it was assumed that supply of an amount of wood that provides 1 kWh by combustion, replaces the consumption of an amount of fossil oil that could provide the same amount of energy by combustion. Hence, the broken curve in Figure 5 represents a limiting case on the optimistic side. With a static approach to the oil market, this would represent a case with a horizontal supply curve for oil (perfectly elastic supply). However, it might be more realistic that the supply of oil is not perfectly elastic, but rather is increasing in the oil price. That would mean less substitution and the final effect on RF of harvest will be *above* the broken curve of Figure 5.

The unbroken curve in Figure 5 shows the net effect of harvesting a single stand, when no substitution of fossil fuels is considered. Hence, the unbroken curve represents the case where the supply of oil is represented by a vertical line (non-elastic supply). Hence, while the broken and unbroken curves represent two limiting, and perhaps unlikely, cases, the real effect of a single harvesting is more likely somewhere in the shaded area in between the two curves. If oil supply is considered to be very elastic, the result is close to the broken curve, while it is close to the unbroken curve if oil supply is relatively non-elastic.

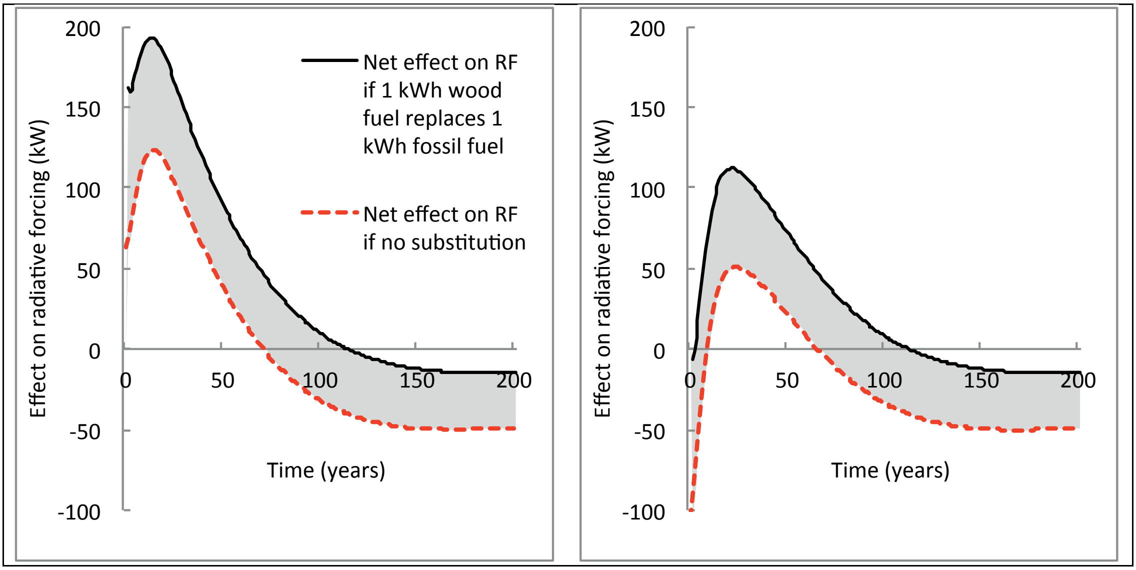

Figure 5. A single harvest event – the oil substitution case. The effect on RF if a stand of age 100 years, as described in Figure 2, is harvested in year t=0. 75 percent of the tops and branches are harvested together with the stems. The entire harvest is used for bioenergy. In the reference scenario, the stand is not harvested. Instead, an amount of fossil oil provides the same energy supply (in kWh). The left diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right diagram.

Comparing the right and left diagram in Figure 5, we see the same results in the long term, but different results in the short term. The differences in the short term appear because the right diagram assumes a significant albedo effect of harvesting, while the left diagram does not. In the albedo case an immediate net cooling effect was found. After that follows a period of net warming, also when substitution is taken into account. However, after 70 – 110 years there will again be a net cooling effect because the stand has regrown. Note that there will be a cooling effect in the long term even in the case with no substitution of fossil fuel consumption. This is because a share of the biogenic carbon released has been absorbed by the sea and the terrestrial biosphere. Hence, in the long term the net effect of the single harvest event is reduced CO_2-concentration in the atmosphere, even in the case where the increased supply of wood fuels does not replace any consumption of fossil fuels.

To have the true effects of a permanently increased use of bioenergy, the multiple harvest approach is in the following considered. This means that harvest events, as described by Figure 3, 4, and 5, take every year from *t*=0 and onwards. Note here, however, that these diagrams show that the considered stand is harvested only once, and not repeatedly after 100 years, and so forth. This is to make the exposition as transparent as possible. Note also, that it is irrelevant for the results whether the stands that are harvested in rotations two, three, and so forth, are the same as those 100 stands that were harvested in the first rotation. The key point is that in every year, a new stand reaches the age of 100 years and is harvested (in the harvest scenario).

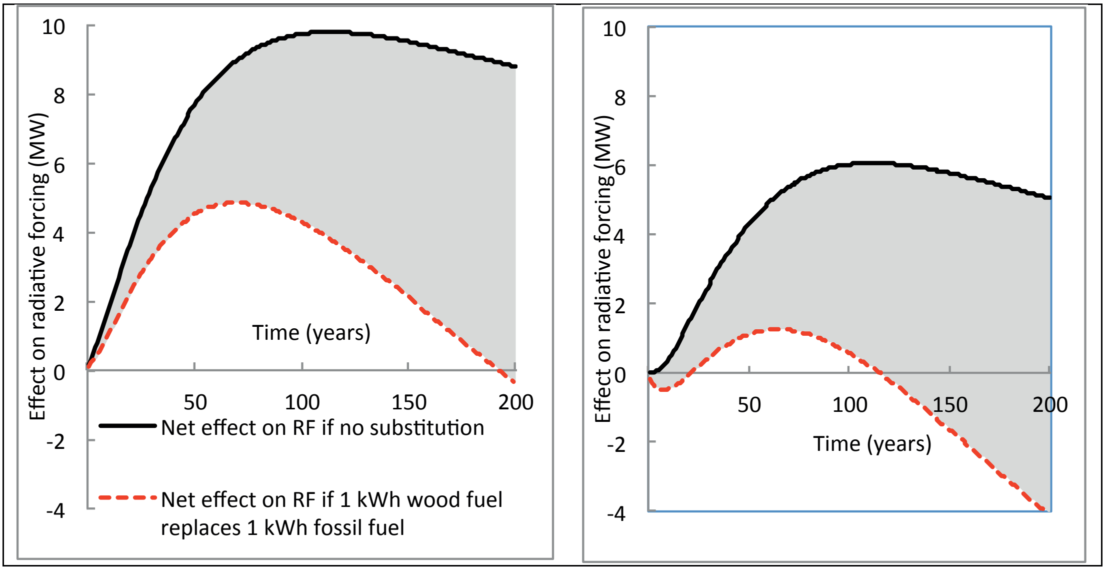

Figure 6. The oil case. The effect on RF if every year from t=0, one stand of age 100 years, each with properties as described in Figure 2, is harvested. The main share (75 percent) of the tops and branches were assumed harvested together with the stems. The entire harvest was used for bioenergy. In the reference scenario the stands are not harvested. Instead fossil oil provides the same energy supply (in kWh). The left diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right diagram.

Figures 6, 7 and 8 display the results of the multi harvest approach. Again the right diagrams assume a significant albedo effect of harvesting, while the left diagrams do not. While Figure 6 shows the case where wood fuels replace fossil oil, Figures 7 and 8 show the cases where wood fuels replace gas and coal, respectively.

First, consider Figure 6, which as Figure 5, reports the results when wood fuels replace fossil oil. Note that using the multiple harvesting approach leads to a significantly different outcome compared to the single harvest approach. Without substitution of fossil fuels (the solid line), there is a warming effect in the whole displayed time span (200 years). And, actually, as reported in Holtsmark (2013b, p 134), there will be a permanent warming effect, if there is no substitution of fossil fuels.

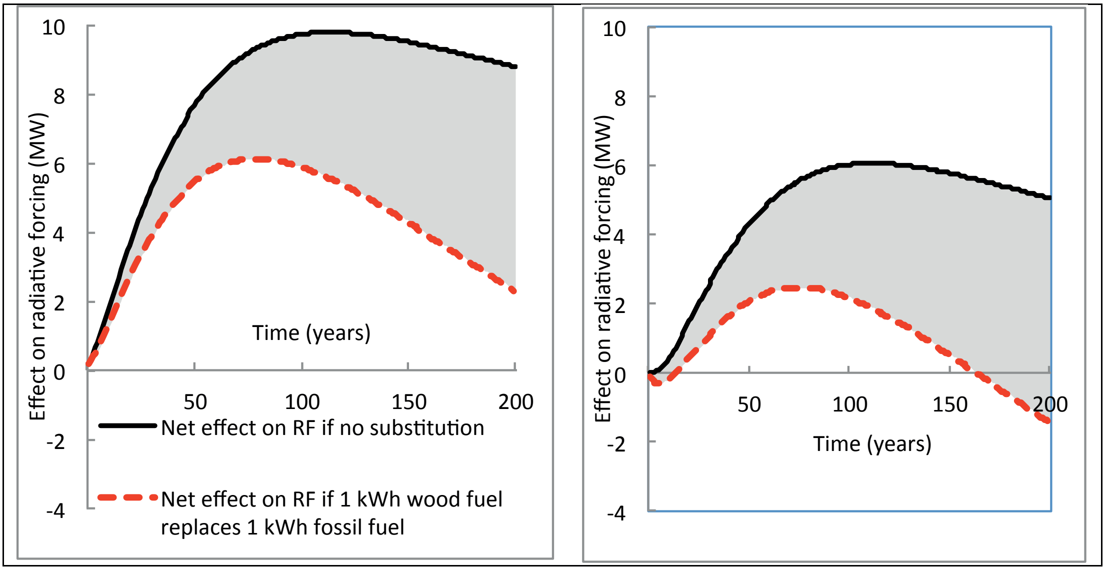

Figure 7. The natural gas case. The effect on RF if every year from t=0, one stand of age 100 years, each with properties as described in Figure 2, is harvested. The main share (75 percent) of the tops and branches were assumed harvested together with the stems. The entire harvest was used for bioenergy. In the reference scenario the stands are not harvested. Instead natural gas provides the same energy supply (in kWh). The left diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right diagram.

When there is substitution of fossil fuels, the results are less clear. If there is full substitution in the sense that 1 kWh of wood fuels replaces 1 kWh of fossil oil, there will be a cooling effect after 185 years in the case without albedo. With increased albedo after harvesting there will be an immediate cooling effect of harvesting, but after approximately 20 years there will be a net warming effect that last until approximately 115 years after harvesting. Recall, however that the broken curve in Figure 6 represents the limiting case with full substitution. More likely, the degree of substitution is smaller, leading to a less favorable result of harvesting somewhere in the grey area between the broken and solid curves.

Figure 7 provides the corresponding results when wood fuels replace natural gas. In the case without albedo effects, there will be a net warming effect of harvesting in the whole considered time span shown in Figure 7. However, after 260 years there will be a cooling effect (not shown in the diagram). In the case with albedo, assuming high degree of substitution, there is a short period after harvesting with net cooling, then net warming for approximately 150 years.

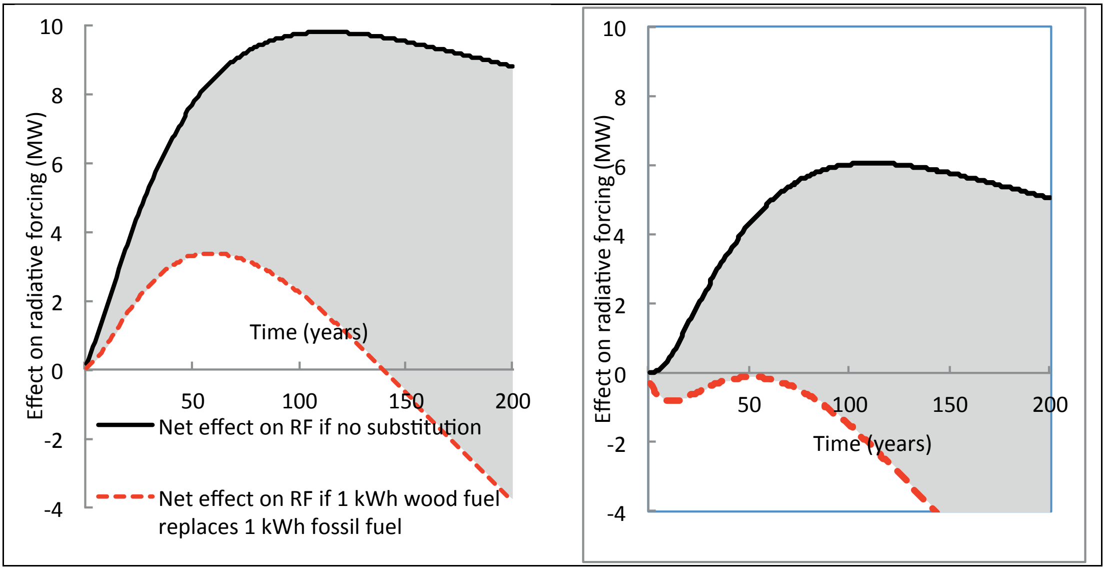

Figure 8. The coal case. The effect on RF if every year from t=0 one stand of age 100 years, each with properties as described in Figure 2, is harvested. The main share (75 percent) of the tops and branches were assumed harvested together with the stems. The entire harvest was used for bioenergy. In the reference scenario the stands are not harvested. Instead coal provides the same energy supply (in kWh). The left diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right diagram.

4 Discussion

Over the last few years a number of studies applied the GWP-concept to quantify the warming impact of combustion of biomass. This paper adopted the method of earlier studies using the GWP concept, but as in Holtsmark (2015) an improved model of the forest stand was applied taking the dynamics of the stand's different carbon pools into account. In addition, the present paper developed the method applied by Holtsmark (2015) further taking albedo changes from harvesting into account in addition to an improved model for decomposition of dead organic matter. However, cases both with and without albedo effects were considered.

When the albedo effect is not accounted for, the estimates of GWP_{bio} are almost identical to the results found in Holtsmark (2015). Hence, with inclusion of an improved model for decomposition of dead organic matter, the conclusions in Holtsmark (2015) are confirmed. Hence, the GWP_{bio} of biomass from a slow growing forest is found to be above 1 if the albedo effects of harvesting are insignificant (Table 1).

When albedo effects are taken into the calculations, the GWP_{bio} estimates become significantly lower. With collection of residues (tops and branches) together with the stems, the GWP_{bio} estimate drops to 0.75, when a time horizon of 100 years was applied. In the case without collection of any residues, GWP_{bio} was found to be 1.1. This is lower than the estimates of GWP_{bio} found in Holtsmark (2015), but higher than the GWP_{bio} estimated by Cherubini, Bright, and Strømman (2012).

To explain the latter difference, a simplified forest stand model was simulated (Table 2). The changes of the model were made in accordance with the model used by Cherubini, Bright, and Strømman (2012), which means no accumulation of naturally dead organic, an abrupt stop in forest growth when the stand age becomes 100 years, no accumulation of carbon in the stand in the no harvest scenario and no release of soil carbon after harvesting. This exercise gave a GWP_{bio} estimate of 0.06 (time horizon of 100 years), in good agreement with the results of Cherubini, Bright, and Strømman (2012), see Table 2.

Next, a comparison of the warming impact of wood fuels and fossil fuels was presented. The result was that when there is no albedo effects of harvesting and either a 100 years or a 20 years time horizon was applied, then the warming impact of wood fuels is significantly higher than the warming impact of fossil fuels (Figure 4). The results are more ambiguous when there is assumed to be an albedo effect of harvesting. The performance of wood fuels compared to fossil fuels then depends on whether residues are collected together with the stems. If residues are collected, the warming effect of wood fuels per unit energy produced is approximately at the level of oil, when a 100 years time horizon is applied (Figure 4, right diagram). If residues are not harvested, the warming effect of wood fuels is approximately at the level of coal, when a 100 years time horizon is applied (Figure 4, left diagram). If a time horizon of 500 years is applied, wood fuels have a smaller warming effect than all three types of fossil fuels irrespective of the assumptions made.

Finally, a landscape approach was taken to find the effects of a permanent increase of the harvest level. Comparisons were made with the warming effect of oil, coal and natural gas. A contribution here is to take into account that the extent to which biofuels actually will reduce the consumption of fossil fuels is an uncertain matter. Therefore, the limiting cases with no substitution and full substitution (1 kWh bioenergy replaces 1 kWh fossil fuels) were considered to see the full range of possible outcomes. The landscape approach gives the possibility to estimate the length of what have been labeled the payback time of the carbon of bioenergy, see Fargione et al. (2008), Dehue (2013), Holtsmark (2012), Jonker, Junginger, and Faaij (2014), Lamers and Junginger (2013), Lapola et al. (2010), Searchinger et al. (2008).

Compared to Holtsmark (2012), it is a methodological improvement that the Bern 2.5CC carbon cycle model is applied instead of simple accumulation of carbon in the atmosphere with no decay function.

It was found that the payback time of the carbon is 140 years if there is full substitution against coal (1 kWh bioenergy replaces 1 kWh coal) and albedo was not taken into account, see left diagram of Figure 8. If bioenergy replaces oil or gas, the pay back time is significantly longer. These results are good agreement with the findings in Holtsmark (2012) who only considered the full substitution case. If less optimistic assumptions were made with regard to how much fossil fuels that are replaced by increased supply of bioenergy, the pay back time becomes longer.

The inclusion of the albedo effects of harvesting gives a picture significantly more in favor of bioenergy, with shorter pay back times. I there is full substitution of coal, the albedo case means that there is a net cooling effect of harvesting from day one. However, if there is less optimistic substitution, the picture is less in the favor of bioenergy, see the gray area of the right diagram in Figure 8.

Finally, some limitations and characteristics of the present study should be emphasized. Most important is to keep in mind that the study considers additional harvesting for the purpose of increasing the supply of bioenergy only. Hence, the paper does not represent an evaluation of harvesting in general. For example, the use of left over biomass from the forest industry is not analyzed in this paper.

Note also that the present paper does not discuss the size of the albedo effects. At this point the assumptions are fully based on Cherubini, Bright, and Strømman (2012) who considered a forest stand located in Hedmark in the south-eastern part of Norway. This is an area with a relative long season with snow cover. Many other districts in Norway have either shorter snow seasons or are located at higher altitudes with a winter with less sun. Hence, most forests in Norway will probably therefore have smaller albedo effects of harvesting.

Moreover, the albedo effect of harvesting is assumed to be the same throughout the simulation period. However, a warmer climate is likely to reduce the season with snow cover significantly during the 21st century. That is not taken into account in the present paper. Hence, the cooling effect of albedo after harvesting may have been exaggerated in the present calculations.

Most LCA-studies have made the assumption that one additional unit of wood fuels will replace the same amount of fossil fuels on a 1 kWh against 1 kWh basis. This is not in correspondence with basic knowledge about how the energy markets perform and probably too optimistic. A contribution of the present paper is to calculate the complete set of possible outcomes when it is taken into account that the fossil fuel markets are poorly understood and that the degree of substitution is difficult to predict. The simulations illustrate clearly that the substitution effect is an important uncertain part of any analysis of the climatic effects of increased use of biofuels. An improvement of the analysis, which is left for future studies, would be to incorporate the energy markets into the model.

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Faustmann and the climate☆

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ABSTRACT

The paper presents an adjusted Faustmann Rule for optimal harvest of a forest when there is a social cost of carbon emissions. The theoretical framework takes account of the dynamics and interactions of forests' multiple carbon pools and assumes an infinite time horizon. Our paper provides a theoretical foundation for numerical model studies that have found that a social cost of carbon implies longer optimal rotation periods and that if the social cost of carbon exceeds a certain threshold value the forest should not be harvested. At the same time we show that it could be a net social benefit from harvesting even if the commercial profit from harvest is negative. If that is the case, the optimal harvest age is decreasing in the social cost of carbon.

Introduction

There has been extensive research on the question of what is optimal forest management when there is a social cost of carbon emissions to the atmosphere. A broadly accepted conclusion from this

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literature is that a social cost of carbon emissions should lead to longer rotation periods and that if the social cost of carbon exceeds a certain level, the considered stand should not be harvested, see for example Asante and Armstrong (2012), Asante et al. (2011), Daigneault et al. (2010), Gutrich and Howarth (2007), Kötke and Dieter (2010), Kaipainen et al. (2004), Price and Willis (2011), Pukkala (2011), Raymer et al. (2011), Farzin and Tahvonen (1996), Tahvonen (1995), Tahvonen et al. (2010), and van Kooten et al. (1995).

While most contributions to this strand of the literature have been based on numerical simulation models, our main contribution is to analyze the issue theoretically with less restrictive assumptions than earlier theoretical studies. In addition, we illustrate the theoretical results with numerical examples. We will show that our less restrictive assumptions turn out to be important for the conclusions.

With regard to theoretical studies of the question of how a social cost of carbon should influence forest management, van Kooten et al. (1995) represent to our knowledge the most thorough study of the issue. They applied a multi-rotation infinite time horizon model and provided an adjusted Faustmann Rule for determination of the length of the rotation period when there is a social cost of carbon emissions. However, the theoretical framework of van Kooten et al. (1995) did not incorporate the dynamics of important carbon pools as roots, stumps, tops and branches, harvest residues and naturally dead organic matter.

Asante and Armstrong (2012) is another theoretical contribution. In contrast to van Kooten et al. (1995) they included the forests' multiple carbon pools in their model. At the same time they considered a single rotation model only and their time horizon was limited to the length of the single rotation. As van Kooten et al. (1995), Asante and Armstrong (2012) found that a social cost of carbon emissions increases optimal harvest age. However, their numerical analysis indicated that incorporating the pools of dead organic matter and wood products in their model have the effect of reducing rotation age. And finally, they found that the higher are the initial stocks of carbon in dead organic matter or wood products the shorter is the optimal harvest age.

Holtsmark et al. (2013) discussed the results of Asante and Armstrong (2012) and Asante et al. (2011) and found that the surprising result that the higher are the initial stocks of carbon in dead organic matter or wood products the shorter is the optimal harvest age, was an artifact of their limited time horizon. Holtsmark et al. (2013) found that from a theoretical point of view the initial stocks of carbon in dead organic matter or wood products should not influence the harvest age. Moreover, the numerical analyses in Holtsmark et al. (2013) indicated that accounting for dead organic matter has the effect of increasing the rotation age, also in contrast to the results of Asante and Armstrong (2012) and Asante et al. (2011).

Although Holtsmark et al. (2013) applied an infinite time horizon, it presented a single rotation analysis only and presented few theoretical results. This underlines the need for a theoretical, multi-period infinite horizon analysis of the issue, which includes the dynamics of the forests' main carbon pools. Therefore, this paper presents a comprehensive theoretical analysis of the question of how a social cost of carbon should influence the length of rotation and the harvest level.

The present paper combines the multi-rotation infinite time horizon model of van Kooten et al. (1995) with the single-rotation, multiple carbon pools approach of Asante and Armstrong (2012) and Holtsmark et al. (2013). Compared to the many numerical model studies of the issue, our theoretical analysis is superior in its potential to reveal the drivers behind the obtained results. While it is generally more difficult to disentangle the important assumptions in a numerical model, our theoretical framework allows us to discuss these more thoroughly.

Our starting point is Faustmann (1849), who has been attributed a formula for determination of the length of the rotation period when a forest owner's goal is to maximize the discounted yield, see also Clark (2010), Samuelson (1976) and Scorgie and Kennedy (1996). We develop an adjusted Faustmann Rule when there is a social cost of carbon emissions, while taking into account the dynamics and interactions of the forest's multiple carbon pools. From this rule it follows if there is a positive commercial profit from harvesting and the socially optimal harvest age is finite, then the optimal harvest age is increasing in the social cost of carbon. If there is a negative commercial profit from harvesting, one cannot on theoretical basis rule out that the socially optimal rotation length is finite. If the socially optimal rotation length is finite in the case with negative commercial profit from harvesting, then the rotation length is decreasing in the size of the social cost of carbon. However, our numerical model indicates that with reasonable levels of the discount rate and other parameters, negative commercial profit means that the optimal rotation length is infinite. The numerical model also indicate that if there is a positive commercial profit from harvesting, and the social cost of carbon exceeds a certain threshold, then the forest should not be harvested. The numerical examples showed that even at quite moderate levels of the social cost of carbon, social welfare is maximized by never harvesting the forest. This last result was also found in the single rotation analysis of Holtsmark et al. (2013). However, a single rotation analysis of the type reported in Holtsmark et al. (2013) will to some extent provide somewhat too high estimates of the effect on the rotation length of a social cost of carbon. The reason is that a single rotation analysis does not take into account the regrowth of the considered stand in later rotations.

To our knowledge, no one has undertaken a full theoretical analysis of optimal forest management in the presence of a social cost of carbon that includes all the following five realistic features, which are all included in our model:

1. Only about half of the carbon in the forests' living biomass is contained in the tree trunks. Tops, branches, roots and stumps constitute the remaining half of the carbon stored in living biomass.
2. Harvest residues will gradually decompose and release carbon to the atmosphere. Moreover, natural deadwood constitutes an important part of the carbon stock of a forest. The dynamics of these carbon pools are included in the analysis.
3. We allow an exogenous fraction of tops, branches, roots and stumps to be harvested and used for energy purposes, and study the consequences of changing this fraction.
4. Tree trunks that are harvested may either be used in a way that immediately releases carbon to the atmosphere (e.g. for energy purposes) or as materials for buildings and furniture. The size of the fraction of the harvest used for such purposes and the lifetime of this carbon stock could be varied. We study different assumptions with regard to these parameters.
5. We apply an infinite time perspective, not only with a single harvest perspective.

Before we embark on the analysis, we should also mention Hartman (1976), who provided an adjusted rule for optimal rotation length. However, he considered a case where a forest provides valuable services in addition to the values provided by timber harvesting and did not focus on a social cost of carbon.

The next four sections present our theoretical model and our main theoretical results. Section "Numerical illustrations" presents numerical examples and section "Discussion and conclusion" concludes. Appendix A contains proofs of our main results, a discussion of how our results would change if some parameters were changing over time, as well as a background discussion of whether the social cost of carbon is rising over time.

A model for calculation of optimal rotation length

We consider a forest stand where the stock of living biomass, measured in units of its carbon content, develops according to the function $B(t)$, where t is the time since last harvest, and $B(0)=0$.[1] In accordance with what is common in the literature we assume that the stock of living biomass increases with age t up to some maximum value $\overline{B} = B(\bar{t})$. In order to simplify the analysis we assume that when $t \geq \bar{t}$, the stock of living biomass is constant, i.e. $B(t) = \overline{B}$ for any $t \geq \bar{t}$. We did not analyze the case where $B(t)$ is decreasing when t exceeds a certain threshold level.

It is assumed that the trunks $R(t)$ constitute a share $\alpha \in (0, 1)$ of the total stock of living biomass $B(t)$. Obviously, this assumption is a simplification. In reality the ratio between stems and total biomass is increasing over time, see e.g. Asante and Armstrong (2012). However, as argued in Appendix A, our assumption of $R(t)/B(t)$ being constant is not important for our results as long as this ratio does not increase rapidly in t for values close to the optimal rotation time.

[1] We assume throughout the paper that the land occupied by the forest has such low value in alternative uses that these are irrelevant.

The forest owner is assumed to harvest a share $\sigma \in [0, 1]$ of the residues in addition to the trunks $R(t)$. Hence, in total a share $\alpha + \sigma(1-\alpha) \in [\alpha, 1]$ of the total living biomass $B(T)$ is harvested, where T is the length of the rotation period. In the formal analysis σ is assumed constant. In reality, marginal harvesting costs of the residues are likely to be increasing in σ, making σ endogenously determined and depending on the price of energy. We return to this issue in the section "The optimal rotation period and the social cost of carbon".

We assume that a share $\beta \in [0, 1]$ of the trunks harvested is used as building materials and furniture. The remaining share of the trunks is used for energy purposes. Note also that we assume that all of the harvested residues are used for energy purposes. The assumption of β being exogenous and independent of T is a simplification. The choice of using trunks for building materials and furniture vs. for energy, will to some extent depend on the size and quality of the trunks. It seems reasonable to believe that more will be used for building materials and furniture the larger is T (Gutrich and Howarth, 2007; Pukkala, 2011). In Appendix A we show that our main results are not changed if β is increasing in T instead of constant.

The relative price between the two uses of trunks may also influence the ratio β: The higher is the price of energy relative to the price of building materials, the lower is β likely to be. This is discussed further in the section "The social optimum".

A further simplification is that net profit per unit harvest (the net price) is assumed independent of T. It is probably more realistic to assume that the net price is increasing in T, at least up to a certain threshold value of T. However, in Appendix A we show that if the net price is increasing in T, it strengthens our main result.

Before we proceed, we list the following stock and flow variables that all are important in the subsequent analysis:

B	the total stock of biomass
$R = \alpha B$	the stock of trunks
$(1-\alpha)B$	residues generated by harvesting
$\sigma(1-\alpha)B$	residues harvested
$(1-\sigma)(1-\alpha)B$	residues left on the stand
$(1-\beta)\alpha B + \sigma(1-\alpha)B$	energy
$\beta\alpha B = \beta R$	building materials

Other relevant stocks of carbon are natural deadwood, as well as the stock of carbon stored in wood-based building materials and furniture with their origin in the considered stand. Below, the dynamics of all these stocks of carbon are modeled.

The present value of the commercial profits from the next harvest is

$$V_P(p, T, \sigma) = e^{-\delta T} p(\alpha + \sigma(1-\alpha))B(T), \quad (1)$$

where $\delta \in (0, 1)$ is the discount rate and p is commercial profit per unit of harvest.[2] Clearly, p will depend on both prices and costs of the two uses of the harvested stand. Changes in e.g. the price of energy are likely to affect p; this is discussed in the section "The optimal rotation period and the social cost of carbon". We assume throughout most of the paper that $p > 0$, but briefly discuss the case of a commercially unprofitable forest ($p \leq 0$) in the section "A commercially unprofitable forest".

We assume that the social cost of carbon emissions is $s(t)$, with the property that the present value $e^{-\delta t}s(t)$ is declining over time. To simplify the formal analysis, we assume that $s(t)$ is constant and equal to s. However, as argued in the concluding section, it is the assumption that the present value of the carbon price is declining over time that is important, not the simplification of $s(t)$ being constant.

With a constant carbon price, the present value social cost of immediate combustion of the harvest that is used for energy is

$$V_F(T, s, \beta, \sigma) = e^{-\delta T} s(\alpha(1-\beta) + \sigma(1-\alpha))B(T). \quad (2)$$

[2] The social value of the harvest is the same as the commercial profits, provided fossil fuel use that is affected by the harvest is taxed according to the social cost of carbon.

At the time of harvest, a stock of building materials and furniture, $M(T)$, is generated; from our assumptions above we have

$$M(T) = \beta\alpha B(T). \quad (3)$$

Within each time period a share $\kappa \in (0, 1)$ of the stock of building materials and furniture is scrapped and combusted. Hence, at time t the remaining stock of building materials/furniture from the first harvest is equal to $e^{-\kappa(t-T)}M(T)$, while emissions at time t due to combustion of this wood are $\kappa e^{-\kappa(t-T)}M(T)$.

Correspondingly, the amount of harvest residues left in on forest floor after a single harvest event is

$$D(T) = (1-\sigma)(1-\alpha)B(T). \quad (4)$$

Within each period, a share $\omega \in (0, 1)$ of the stock of residues left in the forest decomposes. Hence, at time t the remaining stock of residues from the first harvest is equal to $e^{-\omega(t-T)}D(T)$, while emissions at time t due to decomposition of these residues are $\omega e^{-\omega(t-T)}D(T)$. It follows that the present value social cost of these emissions from combustion of building materials and furniture, $V_M(T)$, and from decomposition of residues, $V_D(T)$, are:

$$V_M(T, s, \beta) = \int_T^{\infty} e^{-\delta x} s\kappa e^{-\kappa(x-T)} \beta\alpha B(T)\, dx, \quad (5)$$

$$V_D(T, s, \sigma) = \int_T^{\infty} e^{-\delta x} s\omega e^{-\omega(x-T)} (1-\sigma)(1-\alpha)B(T)\, dx. \quad (6)$$

These expressions are simplified to:

$$V_M(T, s, \beta) = e^{-\delta T} s \frac{\kappa}{\delta+\kappa} \beta B(T), \quad (7)$$

$$V_D(T, s, \sigma) = e^{-\delta T} s \frac{\omega}{\delta+\omega} (1-\sigma)(1-\alpha)B(T). \quad (8)$$

As the stand grows, it will capture and store carbon. The social present value of carbon capture in living biomass over the first rotation is:

$$V_{CC}(T, s) = s \int_0^T e^{-\delta x} B'(x)\, dx. \quad (9)$$

Finally, we have to take into consideration that the stand contains a stock of naturally dead biomass, denoted by $N(t)$, and with $N(0) = 0$. We can here ignore any remaining natural deadwood that might have been generated in earlier rotation periods, see Holtsmark et al. (2013). We assume that the inflow of the stock of natural deadwood is a constant fraction $\gamma \in (0, 1)$ of the living biomass, while the stock decomposes at the same rate as harvest residues. Hence, the accumulation of natural deadwood is:

$$N'(t) = \gamma B(t) - \omega N(t) \quad \text{for} \quad t \in (0, T). \quad (10)$$

Solving the differential equation gives:

$$N(t) = \gamma e^{-\omega t} \int_0^t e^{\omega x} B(x)\, dx, \quad t < T, \quad (11)$$

resulting in:

$$N'(t) = \gamma \left(B(t) - \omega e^{-\omega t} \int_0^t e^{\omega y} B(y)\, dy \right), \quad (12)$$

$$N(T) = \gamma e^{-\omega T} \int_0^T e^{\omega x} B(x)\, dx. \quad (13)$$

At time T, when the stand is harvested, accumulation of a new stock of natural deadwood begins. At the same time, the stock of natural deadwood from the first rotation enters a phase of decomposition (see comment on this below), and we assume that natural deadwood decomposes with the same rate ω as harvest residues.

It follows from (12) that:

$$\lim_{t\to\infty} N'(t) = \gamma\left(\lim_{t\to\infty} B(t) - \omega \lim_{t\to\infty} \frac{e^{\omega t}B(t)}{e^{\omega t}}\right) = 0.$$

Hence, the stock of natural deadwood will approach steady state if the forest is never harvested.

The net accumulation of natural deadwood gives rise to a positive welfare effect through additional carbon capture in the forest. The present social value of carbon capture due to accumulation of natural deadwood during the first rotation period is:

$$V_{NCC}(T, s) = s\int_0^T e^{-\delta x} N'(x)\,dx. \tag{14}$$

In the Appendix (p. 29) of Hoel et al. (2012) we show that this may be written as

$$V_{NCC}(\,\cdot\,) = s\gamma\left(\frac{\delta}{\delta+\omega}\int_0^T e^{-\delta x}B(x)\,dx + \frac{\omega}{\delta+\omega}e^{-(\delta+\omega)T}\int_0^T e^{\omega x}B(x)\,dx\right). \tag{15}$$

Furthermore, the discounted social cost of emissions from decomposition of natural deadwood that was accumulated during the first rotation cycle is:

$$V_{ND}(T, s) = e^{-\delta T} s\int_0^\infty \omega e^{-(\delta+\omega)x} N(T)\,dx.$$

By using (13) we may rewrite this as:

$$V_{ND}(T, s) = s\gamma\frac{\omega}{\delta+\omega}e^{-(\delta+\omega)T}\int_0^T e^{\omega x}B(x)\,dx. \tag{16}$$

Note that the second term on the right hand side of (15) is identical to the right hand side of (16). We may then define the present time social value of net accumulation of natural deadwood:

$$V_N(\,\cdot\,) := V_{NCC}(\,\cdot\,) - V_{ND}(\,\cdot\,), \tag{17}$$

or

$$V_N(\,\cdot\,) = s\gamma\frac{\delta}{\delta+\omega}\int_0^T e^{-\delta x}B(x)\,dx. \tag{18}$$

Summing up, all terms in the net social welfare generated by the first harvest cycle, $V(p, T, s, \beta, \sigma)$, is then:

$$V(p, T, s, \beta, \sigma) := V_P(\,\cdot\,) + V_{CC}(\,\cdot\,) - V_F(\,\cdot\,) - V_M(\,\cdot\,) - V_D(\,\cdot\,) + V_N(\,\cdot\,), \tag{19}$$

where all terms on the right hand side are defined above. Next, define:

$$\Psi(T) := \left(1 + \frac{\gamma}{\delta+\omega}\right)\left(1 - e^{-\delta T} - \delta\frac{\int_0^T e^{-\delta x}B(x)\,dx}{B(T)}\right) \tag{20}$$

$$\Omega := p(\alpha + \sigma(1-\alpha)) + sh \tag{21}$$

where

$$h := (1-\alpha)(1-\sigma)\left(1 - \frac{\omega}{\delta+\omega}\right) + \alpha\beta\left(1 - \frac{\kappa}{\delta+\kappa}\right) \in (0, 1) \tag{22}$$

From the defintions above it follows that we may write:

$$V(\,\cdot\,) = \left[e^{-\delta T}\Omega + s\left((1-e^{-\delta T})\left(1 + \frac{\gamma}{\delta+\omega}\right) - \Psi(T)\right)\right]B(T) \tag{23}$$

Next, define a welfare function including the sum of the discounted welfare of all future rotation cycles:

$$W(p, T, s, \beta, \sigma) := V(\cdot) + e^{-\delta T}V(\cdot) + e^{-\delta 2T}V(\cdot) + \cdots,$$

which is simplified to:

$$W(\cdot) = \frac{1}{1 - e^{-\delta T}}V(\cdot). \tag{24}$$

In preparation for our first result, note that if the rotation period T is increased by one time unit, the first harvest takes place one time unit later, the second harvest two time units later, and so forth. A rule of harvesting simply saying that the growth rate of the stock of stems should drop to the level of the discount rate does not account for this. The contribution of the German forester Faustmann (1849) was to take into account the complete added delay of profits from harvesting when the rotation period is prolonged.

When a social cost on carbon emissions is introduced, similar and additional effects come into play. When increasing the rotation period, the amount of carbon stored on the stand at time of harvesting increases, and emissions from immediate combustion, and from combustion of building materials and furniture, in addition to decomposition of harvest residues, are postponed. And these delays apply to future rotations as well. However, the beginning of the process of carbon capture *after* each harvest is also delayed. Furthermore, the process of accumulation of natural deadwood is affected by increasing the rotation period. In a period of time after harvest there will be net release of C from natural deadwood, as the generation of natural deadwood is small in a young stand. Postponing harvest means an additional period with positive net accumulation of natural deadwood. The trade off between carbon storage now or in the future, as well as between profits now or in the future, determines the optimal length of the rotation period.

For later use, we recall from (21) that $\Omega > 0$ for $p > 0$. Moreover, we show in Appendix A that $\Psi(T)$ is positive and increasing in T for $T < \bar{t}$, and equal to $\Psi(\bar{t})$ for $T \geq \bar{t}$.

The social optimum

To find the social optimum, we differentiate W given by (23) and (24) with respect to T. This is done in Appendix A, where we derive the Lemma 1. Our main theoretical result will follow from this Lemma; an adjusted Faustmann formula taking the social costs of carbon emissions into account:

Lemma 1. *If social welfare $W(p, T, s, \beta, \sigma)$ is maximized for a finite value of T, this value satisfies:*

$$\frac{B'(T)}{B(T)} = \frac{\delta}{1 - e^{-\delta T}}\left(1 - \frac{s}{\Omega}\Psi(T)\right). \tag{25}$$

If

$$\lim_{T\to\infty} W(p, T, s, \beta, \sigma) > W(p, T, s, \beta, \sigma) \text{for all finite } T, \tag{26}$$

then social welfare $W(p, T, s, \beta, \sigma)$ is maximized by never harvesting the stand. A necessary condition for (26) to hold is that

$$\Psi(\bar{t}) > \frac{\Omega}{s}. \tag{27}$$

All functions and parameters in (25)–(27) are defined.

Proof. See Appendix A. □

Condition (27) is simply the condition for the derivative $W_T(p, T, s, \beta, \sigma)$ to be positive for large T. This condition is also sufficient for (26) unless the function $W(p, T, s, \beta, \sigma)$ has a local maximum for $T = T^*$ and a local minimum for $T = T^{**} > T^*$, which seems implausible for reasonable specifications of $B(T)$. In the proceeding discussion we therefore assume that it is optimal to never harvest the stand if and only if the inequality (27) holds.

The l.h.s. of (27) is positive, and can be lower or higher than 1. The fraction Ω/s is monotonically declining in s (for $p>0$), with a lower bound of $h\in(0, 1)$. Depending on the parameters, it may be the case that a finite value of T is optimal no matter how large s is. It may also be the case that there is a threshold value, which we label $\bar{s}$, such that if $s>\bar{s}$, then (27) holds and the stand should not be harvested.

It follows from Lemma 1 (more precisely from Eq. (25)) that if $s=0$, then the rotation period that maximizes social welfare is defined by:

$$\frac{B'(T)}{B(T)}=\frac{\delta}{1-e^{-\delta T}}, \tag{28}$$

which is the classical formula attributed to Faustmann (1849) for maximization of the forest owner's profit. Furthermore, if $s=0$ and the discount rate δ approaches zero, then (25) reduces to

$$\frac{B'(T)}{B(T)}=\frac{1}{T}. \tag{29}$$

If T satisfies (29), then the rotation length gives the maximum sustained yield.

Our next section discusses how the optimal length of the rotation period depends on the size of the social cost of carbon, s.

The optimal rotation period and the social cost of carbon

From Lemma 1 it is easily verified that the optimal T depends on s/Ω, and hence on s/p. For a given ratio of s/p, the optimal T is unaffected by s. We mentioned in the previous section that p might depend on the price of energy, since p is average profit per unit harvest, some of which is used for energy purposes. It is beyond the scope of the present paper to give a full analysis of how prices of energy and other uses of forest harvests may depend on the social cost of carbon. It may nevertheless be useful to illustrate the issue with a very simple example. Let $p=wp_1+(1-w)p_2$ where w is the share of the harvest used for building materials and furniture, assumed for now exogenous.[3] Profits per unit harvest used for building materials and furniture are exogenous and equal to p_1, assumed positive. Profits per unit harvest used for energy are given by $p_2=q+s-c$, where c is the average cost of harvest for energy purposes, and $q+s$ is the energy price. An obvious interpretation is that bioenergy and fossil energy are perfect substitutes, fossil energy is competitively supplied at the unit cost q, and s is a carbon tax on fossil energy only.

With the notation and assumptions above we have

$$\frac{s}{p}=\frac{s}{wp_1+(1-w)(q+s-c)}$$

This relative price will be increasing in s if $wp_1+(1-w)(q-c)>0$. A sufficient condition for this to hold is that $q-c>0$, i.e. that there are positive profits from producing bioenergy even in the absence of any carbon tax. It is not obvious that this holds. In the rest of the paper we shall nevertheless assume that s/p increases when s increases. The results below are changed in obvious ways if the opposite were true.

In the section "A model for calculation of optimal rotation length" we argued that σ and β might depend on s. We return to this below, but first consider the case of a change in s for given values of σ and β.

Our main result concerns the effect on the optimal length of the rotation period of an increase in the social cost of carbon, s:

Proposition 1. *If $p>0$ and the optimal T is finite, the length of the rotation period that maximizes social welfare is strictly increasing in the social cost of carbon, s.*

Proof. See Appendix A. □

[3] It follows from the assumptions in the section "A model for calculation of optimal rotation length" that $w=\frac{\alpha\beta}{\alpha+(1-\alpha)\sigma}$.

This result provides a theoretical foundation for a number of numerical studies that pointed in the same direction. Proposition 1 is also in agreement with the main results of the theoretical models of van Kooten et al. (1995) and Asante and Armstrong (2012) although their models were less general.

The main driver of the result in Proposition 1 is the decreasing present value of the social cost of carbon emissions. If emissions in the future are preferred over emissions today, a higher cost of emissions implies longer optimal rotation periods, since delaying harvest also delays emissions. We show in Appendix A that the optimal length of the rotation period is independent of the social cost of carbon if the present value of this cost is constant over time.

We argued previously that σ, the share of residues that is harvested, might depend on the social cost of carbon, s. Independently of whether or not this is the case, it is of interest to see how an increase in σ affects the optimal length of the rotation period.

Proposition 2. *If and only if the social cost of carbon is sufficiently low relative to the per unit commercial profits from harvest, an increase in the share of the living biomass that is harvested in addition to trunks, σ, will strictly decrease the optimal length of the rotation period.*

Proof. In Appendix A, we show that the optimal rotation period, T, is strictly decreasing in σ if and only if

$$\frac{s}{p} < \frac{\delta+\omega}{\delta}. \tag{30}$$

□

If the inequality in (30) does not hold, the optimal length of the rotation period will either be increased or unaffected by an increase in σ. An increase in σ means that more biomass is harvested and used for energy purposes, and less harvest residues are left in the forest. The result is that both commercial profits and emissions immediately after harvest are increased. If the per unit profit is large enough, this decreases the optimal length of the rotation period. However, if the social cost of carbon emissions is large compared to the per unit profit, the optimal length of the rotation period is increased.

Assume that due to increased profitability of bioenergy, σ is an increasing function of s. From Proposition 2 we know that if s is sufficiently high, an increase in σ will make T go up (or stay unchanged). In this case σ increasing with s thus strengthens our conclusion that T increases with s. However, for lower values of s we get the opposite: an increase in σ will make T go down. If σ increases with s the total effect of an increase in s hence has a theoretically ambiguous effect on T. The direct effect is to increase T (Proposition 1), while the indirect effect via a higher σ tends to reduce T (Proposition 2). In our numerical illustration in the section "The optimal rotation period and the social cost of carbon" we find that for reasonable assumptions about how much σ is affected by a change in s, the direct effect dominates. Hence, for this case Proposition 1 remains valid.

We argued previously that β, the share of trunks used for building materials and furniture, might depend on the social cost of s. Independently of whether or not this is the case, it is of interest to see how an increase in β affects the optimal length of the rotation period.

Proposition 3. *If the optimal T is finite, an increase in β, the share of trunks used for building materials and furniture, will strictly reduce the optimal length of the rotation period, T.*

Proof. See Appendix A. □

When a larger share of harvested biomass is used for building materials and furniture, emissions immediately following harvest are reduced. This implies a smaller social gain from postponing harvest, and hence a shorter optimal rotation period.

Assume that due to increased profitability of bioenergy, β is a decreasing function of s. From Proposition 3 we know that a reduction in β will make T go up. It follows that β decreasing with s strengthens our conclusion from Proposition 1 that T increases with s.

We conclude this section by considering the limiting case of no residuals ($\alpha = 1$), and all the harvested stems are stored in a safe place forever ($\beta = 1$ and $\kappa = 0$). In this case there is no release of carbon after harvesting, so we might expect that the optimal T is finite for all values of s in this case. It is straightforward to see that $\Omega = p + s$ for this case, implying $\Omega/s = (p + s)/s$, which has a lower bound equal to 1. If $\Psi(\bar{t}) \le 1$, the inequality in (27) can therefore not hold no matter how high s is, implying that the optimal T is finite for all values of s. However, due to the growth of deadwood ($\gamma > 0$), we cannot theoretically rule out the possibility of $\Psi(\bar{t}) > 1$. If this inequality holds and s is sufficiently large, it will be optimal to never harvest the forest. The interpretation of this is that with a sufficiently large value of s, the importance of deadwood growth for social welfare will be so high that the forest should never be harvested.

A commercially unprofitable forest

If $p \le 0$, there will be no profit from harvesting an existing forest (disregarding alternative uses of the land, see footnote 1). Leaving the forest unharvested is also socially optimal as long as $s = 0$. However, we shall see below that this may no longer be true if s is positive.

Consider first the case of s positive but so small that $\Omega \le 0$. In this case (27) must hold, implying that it is optimal to never harvest the stand.

Consider next the case of $p \le 0$ and s so large that $\Omega > 0$. From (21) it is clear that Ω/s is monotonically increasing in s in this case, with an upper bound equal to $h \in (0, 1)$. (If $p = 0$, $\Omega/s = h$ for all values of s.). For a sufficiently high value of s, the inequality (27) may therefore no longer hold, and the optimal T may hence be finite.

To interpret the possibility of a finite T being socially optimal for a commercially unprofitable forest, it is useful to return to the limiting case discussed in the end of the section "The optimal rotation period and the social cost of carbon": With no residuals ($\alpha = 1$) and all the harvested stems stored in a safe place forever ($\beta = 1$ and $\kappa = 0$) there is no release of carbon after harvesting. Harvesting and replanting in this case acts as carbon sequestration device and may be optimal if s is sufficiently large. Formally, $\Omega/s = (p + s)/s \in (0, 1)$. It therefore follows from Lemma 1 that a finite T is socially optimal if s is sufficiently high and $\Psi(\bar{t}) < 1$.

Proposition 1 showed us how T depends on s for the case of $p > 0$. For the case of $p \le 0$ we have the following proposition:

Proposition 4. *If $p \le 0$ and the optimal T is finite, the length of the rotation period that maximizes social welfare is strictly decreasing in the social cost of carbon, s, for $p < 0$, and independent of s for $p = 0$.*

Proof. See Appendix A. □

For the optimal T to be finite in the case when $p < 0$, the discount rate has to be relatively low. According to simulations with the numerical model applied in the next section, and assuming that $p < 0$, $\alpha = 0.48$, $\beta = 1$, and $\kappa = 0$, then, for any discount rate equal to or larger than 0.011, the optimal T is infinite for any $s > 0$. Note that this applies also when the stems harvested are stored on a safe place forever ($\beta = 1$ and $\kappa = 0$). If we instead, more realistically, assumed that $\beta = 0.25$ and $\kappa = 0.014$, then, for any discount rate equal to or larger than 0.0001, the optimal T is infinite for any $s > 0$. Hence, with discount rate levels that are usually applied, the forest should not be harvested if there is a negative commercial profit from harvesting.

Numerical illustrations

In order to provide further intuition to the theoretical results in the sections "A model for calculation of optimal rotation length" and "The social optimum", this section provides numerical simulations of the consequences of implementation of a social cost of carbon for optimal harvest from a forest stand. We will in this section only consider cases where the social cost of carbon is constant over time.

Model and parameter values

Fig. 1 provides an overview of the dynamic development of the considered forest stand with 150 years long rotations. Below follows a detailed description of the model.

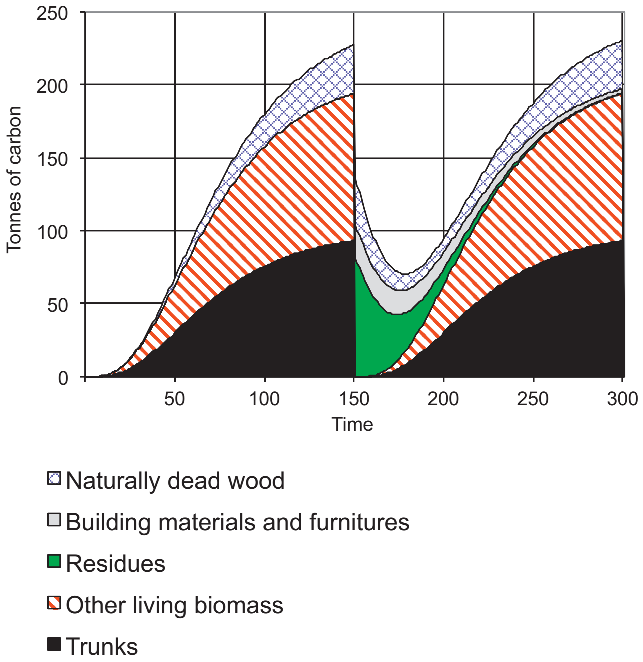

Fig. 1. The development of the components of the stock of carbon in the forest and in building materials/furniture with a rotation length of 150 years.

After harvest at time $t = 0$ the stock of stems is assumed to develop along the function

$$R(t) = \nu_1 (1 - e^{-\nu_2 t})^{\nu_3}.$$

We have followed Asante et al. (2011) in choice of parameter values, which are as follows: $\nu_1 = 100.08$, $\nu_2 = 0.027$, $\nu_3 = 4.003$. (Note that as Asante et al. (2011) applied m^3/ha as their unit of measurement, $\nu_1 = 500.4$ in their set up.) The chosen numerical representation gives maximum sustained yield at 88 year old stands. Hence, it is representative for a Scandinavian forest where the dominating spruce and pine forests typically are mature after 80–110 years. With regard to development of the stock of other living biomass, it is assumed that the trunks constitute 48 percent of total biomass in the forest stand, i.e. $\alpha = 0.48$ (NCPA, 2010).

With regard to the stock of natural deadwood, it is assumed that $\gamma = 0.001$, see Eq. (10) for definition. This parameter value gives an accumulation of natural deadwood corresponding to what is found in Asante et al. (2011). The decomposition rate for deadwood, ω, is set to 0.04 (Holtsmark, 2012).

With regard to the share β of the harvested stems that are used for building materials and furniture, based on NCPA (2011) it is assumed that $\beta = 0.25$ in the base case. However, simulations are provided where other values of this parameter is applied. We have assumed that building materials and furniture are durable goods in the sense that only a share $\kappa = 0.014$ of this stock of wood is scrapped and combusted annually.

The amount of residues harvested is determined by the share σ, which is set to 0.2 in the base case. However, additional simulations are carried out considering higher and lower assumptions with regard to the value of σ. Fig. 1 provides a description of how the different components of the considered stand's carbon stock develops if the rotation length is 150 years.

In the simulations presented in the next subsection it is assumed that the forest owner's net profit is 15 USD/m^3 wood harvested. As one cubic meter of wood contains approximately 0.2 t carbon, this corresponds to 75 USD/tC, for short labeled the (net) price of wood. Note that only the relative price of the social cost of carbon, s/p, matters.

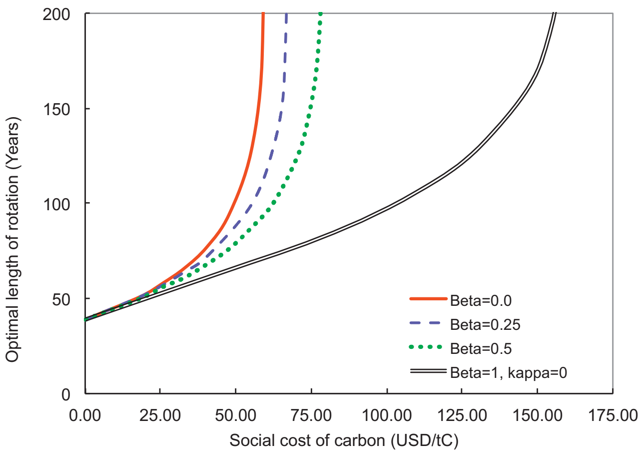

Fig. 2. The optimal length of the rotation period given different shares of the harvest that are used for durable storage in buildings and furniture (β). The net commercial profit to the forest owner is 15 USD/m^3 wood, which corresponds to 75 USD/tC. Hence, $s/p = 1$ if the social cost of carbon is 75 USD/tC. In the cases where β is 0.0, 0.25, and 0.5, then κ is 0.04. In the case where β is 1.0, then $\kappa = 0.0$.

The discount rate is set to 0.05 in all simulations.

Simulation results

Fig. 2 shows the results of simulations carried out in a case where 20 percent of residues are harvested ($\sigma = 0.2$). The solid single-lined curve shows the case where $\beta = 0$, i.e. the share of the harvested stems that are used for building materials and furniture is zero. The dashed curve shows the case where $\beta = 0.25$, while the dotted curve shows the case where $\beta = 0.5$. In addition, the double-lined curve shows for illustrative purposes the less realistic case where all harvested roundwood is stored forever.

The curves in Fig. 2 confirm the result of Proposition 2, that increasing the social cost of carbon s should lead to longer rotation periods. This applies also in the case where a reasonable share of the harvested stems in some way or another are converted to a durable carbon storage, i.e. when $\beta > 0$. In addition, Fig. 2 illustrates that increasing β, i.e. the share of the harvested stems that are used for building materials and furniture, has a significant effect and draws in the direction of shorter rotation. The double-lined curve shows illustrates that the theoretical results of Lemma 1 and Proposition 1 applies also when $\beta = 1$ and $\kappa = 0$.

Table 1 presents results of a number of model simulations given different levels of the share of residues that is harvested as well as different levels of the social cost of carbon. In these simulations it was assumed that the share β of the harvested trunks that are used as building materials and furniture is fixed at 0.25, as this is likely to be close to a realistic level (NCPA, 2011). Table 1 shows that the optimal length of the rotation period is influenced by the share of the residues that are harvested. However, changes in the social cost of carbon have a significantly stronger effect on the optimal rotation length than the size of the share of residues harvested. One should at this point also have in mind that we ignored that the amount of residues harvested is likely to influence the carbon balance of the soil. Intensive removal of residues from the forest floor might lead to release of soil carbon to the atmosphere. The carbon stock of the soil constitutes a significant share of the carbon stock of boreal and temperate forests (Kasischke, 2000). Hence, this effect might be significant (Nakane and Lee, 1995; Palosuo et al., 2001; Nilsen et al., 2008; Repo et al., 2011). Moreover, as mentioned in the section "A model for calculation of optimal rotation length", we assumed that the unit costs related to harvesting of residues are constant to scale and that the commercial profit from harvesting residues is as high as the commercial profit from harvesting stems (per m^3). These simplifications have a common bias and

Table 1
Optimal length of the rotation period (T) with regard to different values of the social cost of carbon (s), as well as different values of the share of residues harvested (σ).[a]

Social cost of carbon		The share of residues harvested (σ)		
s/p	USD/tC	0	0.25[b]	0.50[c]
0	0	39	39	39
0.49	36.67	75	66	61
0.73	55.00	125	96	83
1.00	75.00	∞	∞	176
1.22	91.70	∞	∞	∞

[a] The share of the harvested trunks that are used for durable storage in buildings and furniture (β) is set to 0.25 in all simulations presented in this table.
[b] σ = 0.25 means that all tops and branches are harvested.
[c] σ = 0.5 means that a share of stumps and roots is harvested in addition to tops and branches.

draw in the direction of too high estimates of to what extent increasing the share of residues harvested should reduce the rotation period.

Both Table 1 and Fig. 2 illustrate that the social carbon cost has a certain threshold value above which the stand should not be harvested. The higher is the share of the harvest stored in furniture and buildings, the higher is the mentioned threshold value.

It is here appropriate to recall that only the size of the social cost of carbon *relative* to the price of wood (s/p) matters. Hence, if we for example are considering a marginal forest in the sense that the commercial profit from harvesting is low, then the threshold value of the social cost of carbon, above which the forest should not be harvested, is lower than found in the presented simulation. And correspondingly, if we consider a forest with high commercial profit from harvesting, the threshold value is higher than found here.

In this paper we have emphasized the importance of taking account of the forests' different carbon pools, not only the trunks. Fig. 3 shows the importance of this. The solid curve in Fig. 3 shows the estimates of optimal rotation period in the case where all carbon pools other than the trunks are ignored. The dotted curve shows the estimates when only the trunks and the pool of wooden products are included. Finally, the dashed curve shows the result when all carbon pools are taken account of. The figure shows that these choices influence the estimates of the optimal rotation period significantly. The inclusion of the wood product pool means shorter rotation and a higher threshold value above which the forest should not be harvested. Inclusion of harvest pools as other living biomass than the

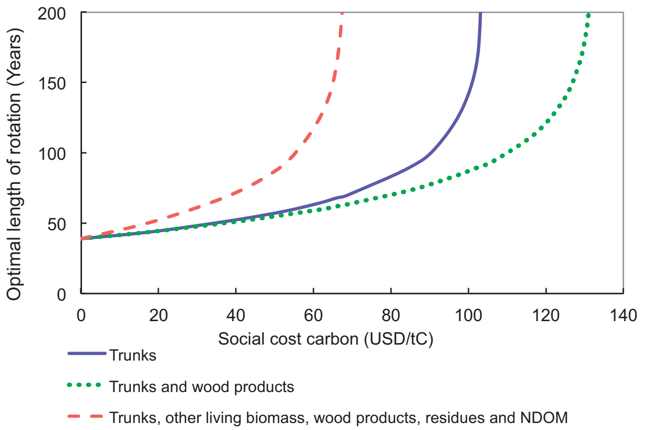

Fig. 3. The optimal length of the rotation period in the main multiple carbon pool case (the double lined curve) and cases where one or more carbon pools are not included in the analysis.

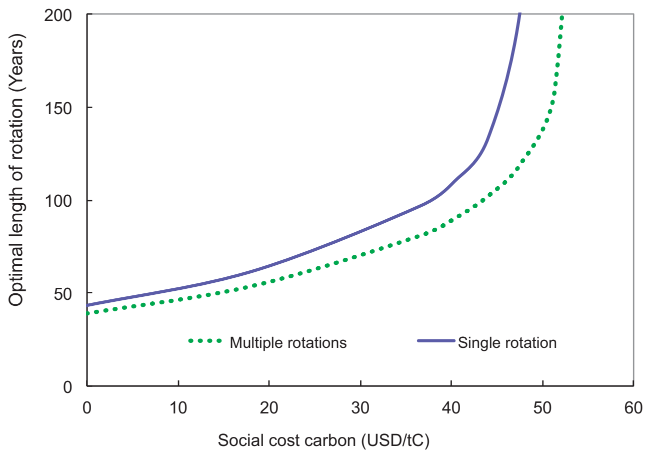

Fig. 4. The optimal long run average annual supply of wood per hectare given different social costs of carbon in a single harvest analysis and when multiple rotations are considered.

stems, harvest residues and NDOM draws in the direction of significantly longer rotation periods and a significantly lower threshold value above which the forest should not be harvested.

As mentioned in the section "Introduction", our results with regard to the effects of inclusion of dead organic matter in the analysis contrast the main finding in Asante and Armstrong (2012) and Asante et al. (2011). They found that incorporating dead organic matter has the effect of reducing the rotation period. In addition, they found that high initial stocks of dead organic matter and wood products have the effect of reducing the rotation period. With regard to the latter result, Holtsmark et al. (2013) demonstrated that it follows from the consideration of a single rotation period only and the fact that Asante and Armstrong (2012) and Asante et al. (2011) ignored the release of carbon from decomposition of dead organic matter after the time of the first harvest *T*. With that simplification it is obvious that a large initial stock of dead organic matter draws in the direction of earlier harvest. Holtsmark et al. (2013) demonstrated that if it had been taken into account that the time profile of the decomposition of the initial carbon pools over the infinite time horizon $t\epsilon(0, \infty)$ is not influenced by the harvest age, the size of the initial carbon pools has no effect on the optimal harvest age. The first mentioned result in Asante and Armstrong (2012) and Asante et al. (2011) with regard to the effects of incorporating multiple carbon pools in the analysis should also be considered in the light of their fail to see the importance of the release of carbon from dead organic matter after time *T*.

An interesting question is how the choice of a single rotation vs. a multiple rotation analysis influence the relationship between the social cost of carbon and the optimal length of the rotation period. Direct comparison of the results reported by Holtsmark et al. (2013) with the results reported here is not fruitful because Holtsmark et al. (2013) included a fixed harvest costs that for simplicity has not been included in this paper's analysis. However, Fig. 4 makes a comparison of a multiple harvest case and a single harvest case, with all other things being equal. It shows that the single rotation analysis to some extent will exaggerate the effect of the social cost of carbon with regard to the optimal harvest age. The intuition behind this result is that the single harvest analysis does not take into account the regrowth in the forest in future rotation periods.

Discussion and conclusion

The increasing use of subsidies in order to encourage the use of biofuels, including wood fuels from forests, calls for a theoretical clarification of how a social cost of carbon should influence forest management. Searchinger et al. (2009) claimed that current regulation regimes might lead to over-harvesting of the world's forests. In order to increase insight, this paper provides a theoretical model of the relationship between forest management and the interaction and dynamics of the forest's multiple carbon pools. A theoretical study that includes the dynamics of the forest's main carbon pools in a multiple rotation infinite horizon model is to our knowledge new. The theoretical analysis leads to an adjusted Faustmann Rule for optimal harvest when there is a social cost of carbon emissions.

Let us first consider the case when there is a positive net commercial profit from harvesting ($p > 0$). In that case, and if the rotation period that maximizes social welfare is finite, the adjusted rule implies that the optimal T is strictly increasing in the social cost of carbon, s. Depending on the parameters, it may be the case that a finite value of T is optimal no matter how large s is. It may also be the case that there is a threshold value, which we labeled $\bar{s}$, such that if $s > \bar{s}$, then the stand should not be harvested. It could here be mentioned that the numerical simulations show that if the discount rate is not lower than 0.01, any realistic set of parameter values of our numerical model gives the conclusion that such a threshold value exists above which the forest should not be harvested.

Next, consider the case when there is negative commercial profit from harvesting ($p < 0$). If s positive but below a certain threshold level (such that $\Omega \leq 0$), then it is optimal to never harvest the stand. If s is above the mentioned threshold level, (such that $\Omega > 0$), depending on the parameters, it could be optimal to harvest, i.e. the rotation period that maximizes social welfare might be finite. If the optimal T is finite when $p < 0$, then the adjusted Faustmann Rule implies that the optimal T is strictly *decreasing* in the social cost of carbon, s. A finite optimal T when $p < 0$ is not a very likely case, however. Numerical simulations showed that if the discount rate is 0.01 or above, and $p < 0$, any realistic set of parameter values of the applied numerical model gives the conclusion that the stand should never be harvested.

The main driver of these results is the assumption that the present value of the climate damage caused by emissions is decreasing over time – emissions in the future are preferred over emissions today. This seems a reasonable assumption, and is elsewhere in the literature often either assumed or derived from other assumptions of the analyses.[4] A single harvest leads to an increase in the stock of carbon in the atmosphere in the short run, and the damage resulting from this increase would have been postponed with a longer rotation period. In order to focus on the main driver of the results, we have chosen to model the social cost of carbon, $s(t)$, as constant over time, giving a declining present value of the damage from emissions. Compared to using a general social cost function $s(t)$, this simplifies the calculations, while still allowing the timing of emissions to affect the optimal rotation period. Intuitively, if the decline in the present value of the social cost of carbon is slower, the effect of this cost on the optimal rotation period is weaker. It can in fact be shown (see Hoel et al., 2012) that in the (unrealistic) limiting case of the present value of $s(t)$ being constant over time, the optimal rotation period is independent of the *level* of $s(t)$, provided this rotation length is finite.

Compared to other theoretical studies, our contribution is to investigate this issue in a considerably less restrictive theoretical framework. We take into account that less than half of the carbon in the forests' biomass is contained in the tree trunks. Tops, branches, roots and stumps constitute approximately half of the carbon stored in living biomass, and to the extent that these components are not harvested together with the trunks, they will gradually decompose and release carbon to the atmosphere. The dynamics of these carbon pools as well as the stock of natural deadwood is included in both the theoretical and numerical analyses. In addition, we allow an exogenous fraction of tops, branches, roots and stumps to be harvested and used for energy purposes. And finally, the dynamics of a stock of carbon stored in building materials and furniture is also taken into account.

With our less restrictive approach, including both multiple rotation periods and multiple carbon pools in the analysis, the threshold value of the social cost of carbon above which harvest should not take place, is significantly lower than found in studies with a more restrictive approach. The multiple carbon pool approach also means that the effect of a social cost of carbon on the length of the rotation period is significantly stronger than found in previous studies. Our model allows us to investigate the effect of changes in the composition and dynamics of forests. In order to fully understand the mechanisms underlying the effect on the rotation period of a social cost of carbon, a model that is

[4] According to Allen et al. (2009), the peak temperature increase due to greenhouse gas emissions is approximately independent of the timing of emissions. However, we would expect this peak temperature increase to occur earlier the more of the emissions occur at an early stage. It seems reasonable to expect climate costs to be higher the more rapidly the temperature increases, for a given peak temperature increase. Hence, it seems reasonable to assume that early emissions are worse than later emissions.

not too restrictive is useful. We have found that increasing the share of residues harvested and/or the share of stems used for durable storage in buildings and furniture reduces the effect of a social cost of carbon on the optimal rotation period. Conclusions regarding the effect on the optimal rotation periods of changes in harvesting procedures or use of harvested material might potentially have important policy implications.

Finally, it should be noted that all conclusions in the paper are based on the implicit assumption that there is a tax or similar instrument related to combustion of fossil fuels, that corresponds to the social cost of carbon. A general equilibrium approach is needed in order to evaluate optimal second-best policy if this is not the case.

Appendix A.

Proofs

Properties of the function $\Psi(T)$

Applying l'Hospital's rule to (20) we find that

$$\lim_{T\to 0}\left(1-e^{-\delta T}-\frac{\delta}{B(T)}\int_0^T e^{-\delta x}B(x)\,dx\right) = -\lim_{T\to 0}\frac{\delta e^{-\delta T}B(T)}{B'(T)} = 0. \tag{A.1}$$

Hence, as T approaches 0, also $\Psi(T)$ approaches zero. Moreover, we have:

$$\Psi'(T) = \left(1+\frac{\gamma}{\delta+\omega}\right)\frac{B'(T)}{(B(T))^2}\int_0^T e^{-\delta x}B(x)\,dx. \tag{A.2}$$

Since $B'(T)>0$ for $T<\bar{t}$ and $B'(T)=0$ for $T\geq\bar{t}$, it follows that $\Psi(T)$ is positive and increasing in T for $T<\bar{t}$, and equal to $\Psi(\bar{t})$ for $T\geq\bar{t}$.

Proof of Lemma 1. We want to find the T that maximizes $W(p, T, s, \beta, \sigma)$. From (23) and (24) we have:

$$W(\cdot) = \frac{1}{1-e^{-\delta T}}\left[e^{-\delta T}\Omega + s\left((1-e^{-\delta T})\left(1+\frac{\gamma}{\delta+\omega}\right)-\Psi(T)\right)\right]B(T) \tag{A.3}$$

Define:

$$\Delta_1 := \Omega B'(T) + \frac{\delta}{1-e^{-\delta T}}(s\Psi(T)-\Omega)B(T). \tag{A.4}$$

Then we could write the first order condition:

$$\frac{\partial W(p,T,s,\beta,\sigma)}{\partial T} = \frac{1}{e^{\delta T}-1}\Delta_1 = 0, \tag{A.5}$$

which gives (25). Furthermore, the inequality in (27) is equivalent to $\Delta_1>0$ for $T\geq\bar{t}$, and hence a necessary condition for

$$\frac{\partial W(p,T,s,\beta,\sigma)}{\partial T} > 0 \tag{A.6}$$

for all $T>0$. If this inequality applies for all $T>0$, then the first order condition (25) does not hold for any $T>0$, and social welfare is maximized by never harvesting. □

Proof of Proposition 1. From (A.5) it follows that the second order condition for the maximization problem can be written as:

$$\frac{\partial^2 W(p,T,s,\beta,\sigma)}{\partial T^2} = \frac{\partial}{\partial T}\left(\frac{1}{e^{\delta T}-1}\right)\cdot\Delta_1 + \frac{1}{e^{\delta T}-1}\cdot\frac{\partial \Delta_1}{\partial T} \leq 0. \tag{A.7}$$

It follows from the first order condition (A.5) that $\Delta_1 = 0$. Hence, the second order condition is reduced to $\partial\Delta_1/\partial T \leq 0$. Define:

$$\Delta_2 := \frac{\partial \Delta_1}{\partial T}.$$

By use of (A.5) we have that:

$$\Delta_2 = \left(\frac{\delta}{e^{\delta T}-1}B'(T) - \frac{(B'(T))^2}{B(T)} + B''(T)\right)\Omega + \frac{\delta}{1-e^{-\delta T}}s\Psi'(T)B(T).$$

Furthermore, when taking the derivative of (25) with respect to s, we find that:

$$\frac{\partial T}{\partial s} = \frac{1}{\Delta_2}\frac{\delta}{1-e^{-\delta T}}\left(\frac{s}{\Omega}\frac{\partial \Omega}{\partial s} - 1\right)\Psi(T)B(T). \tag{A.8}$$

We want to show under what conditions $\partial T/\partial s > 0$. From the second order condition (A.7) we have that $\Delta_2 < 0$. Moreover, we know that have that $\Psi(T)B(T) > 0$. It follows that

$$sign\left(-\frac{\partial T}{\partial s}\right) = sign\left(\frac{s}{\Omega}\frac{\partial \Omega}{\partial s} - 1\right)$$

From (21) it is immediately clear that (for $\Omega > 0$, which must hold for the optimal T to be finite)

$$\frac{s}{\Omega}\frac{\partial \Omega}{\partial s} - 1 > 0 \quad \text{for} \quad p < 0,$$

$$\frac{s}{\Omega}\frac{\partial \Omega}{\partial s} - 1 = 0 \quad \text{for} \quad p = 0,$$

$$\frac{s}{\Omega}\frac{\partial \Omega}{\partial s} - 1 < 0 \quad \text{for} \quad p > 0.$$

It follows that

$$\frac{\partial T}{\partial s} < 0 \text{ for } p < 0,$$

$$\frac{\partial T}{\partial s} = 0 \text{ for } p = 0,$$

$$\frac{\partial T}{\partial s} > 0 \text{ for } p > 0.$$

□

Proof of Proposition 2. In line with the proof of Proposition 1, taking the derivative of (25) with respect to σ and rearranging yields:

$$\frac{\partial T}{\partial \sigma} = \frac{\delta}{1-e^{-\delta T}}\frac{1}{\Delta_2}\frac{s\Psi(T)}{\Omega^2}\frac{\partial \Omega}{\partial \sigma}. \tag{A.9}$$

We have that:

$$\frac{\partial \Omega}{\partial \sigma} = (1-\alpha)\left(p - s\left(1 - \frac{\omega}{\delta+\omega}\right)\right)\begin{cases} > 0 & \text{if } s/p < \dfrac{\delta+\omega}{\delta} \\ \leq 0 & \text{if } s/p \geq \dfrac{\delta+\omega}{\delta}, \end{cases} \tag{A.10}$$

and it follows that

$$\frac{\partial T}{\partial \sigma}\begin{cases} <0 & \text{if } s<\dfrac{\delta+\omega}{\delta} \\ \geq 0 & \text{if } s\geq\dfrac{\delta+\omega}{\delta}, \end{cases} \tag{A.11}$$

which is equivalent to the statement in Proposition 2. □

Proof of Proposition 3. In line with the proof of Propositions 1 and 2, taking the derivative of (25) with respect to β and rearranging yields:

$$\frac{\partial T}{\partial \beta}=\frac{\delta}{1-e^{-\delta T}}\frac{1}{\Delta_2}\frac{s\Psi(T)}{\Omega^2}\frac{\partial \Omega}{\partial \beta}. \tag{A.12}$$

We have that:

$$\frac{\partial \Omega}{\partial \beta}=s\alpha\left[1-\frac{\kappa}{\delta+\kappa}\right]>0 \tag{A.13}$$

Since $\Delta_2<0$ and $\Psi(T)>0$, it follows that $\partial T/\partial \beta<0$, which is equivalent to the statement in Proposition 3. □

Time-dependent prices and parameters

In the section "Introduction" we argued that p, α and β might be increasing functions of the rotation period T. We wish to investigate what implications such extensions may have for our main result given in Proposition 1, i.e. that the optimal rotation time increases with an increased carbon price.

Let p, α and β be replaced with increasing functions $p(T)$, $\alpha(T)$ and $\beta(T)$. The welfare function that is maximized is now instead of (15) given by

$$\Gamma(T,s)\equiv W(T,p(T),s,\alpha(T),\beta(T),\sigma)=\frac{1}{1-e^{-\delta T}}V(T,p(T),s,\alpha(T),\beta(T),\sigma) \tag{A.14}$$

The optimal choice of T (assuming it exists) is given by

$$\Gamma_T(T,s)\equiv W_T+[W_p p'(T)+W_\alpha \alpha'(T)+W_\beta \beta'(T)]=0$$

Differentiating gives

$$\frac{dT}{ds}=\frac{\Gamma_{Ts}}{-\Gamma_{TT}}$$

From the second-order conditions for an optimum we have $\Gamma_{TT}<0$, implying that

$$sign\left(\frac{dT}{ds}\right)=sign(\Gamma_{Ts})$$

Moreover,

$$\Gamma_{Ts}=W_{Ts}+[W_{ps}p'(T)+W_{\alpha s}\alpha'(T)+W_{\beta s}\beta'(T)] \tag{A.15}$$

We showed in Proposition 1 that the optimal T was an increasing function of s when p, α and β were independent of T, i.e. that $W_{Ts}>0$. We now turn to the three terms in square brackets in (A.15)

W_{ps} has the same sign as V_{ps}; by examining each term in the expression for V (given by (19)) we find that $V_{ps}=0$. Hence, the fact that p may be increasing in T does not affect our conclusion that T is increasing in s.

$W_{\alpha s}$ has the same sign as $V_{\alpha s}$; by examining each term in the expression for V (given by (19)) we find that $V_{\alpha s}$ consists of two negative terms (associated with $+V_{CC}$ and $+V_{NCC}$) and three positive terms (associated with $-V_F$, $-V_D$ and $-V_N$). More specifically, we have that

$$V_{\alpha s}=\frac{1}{\alpha^2}\left[e^{-\delta T}\frac{\omega+\sigma\delta}{\delta+\omega}B(T)-\int_0^T e^{-\delta x}B'(x)\,dx+\gamma\int_0^T\left(e^{-\delta T}\frac{\omega}{\delta+\omega}-e^{-\delta x}\right)B(x)\,dx\right]. \tag{A.16}$$

With regard to the terms in the square bracket above, the first term is less than the second term, while the third term is less than the fourth term. Hence, $V_{\alpha s} < 0$, implying that we cannot rule out the possibility that $\alpha'(T) > 0$ may reverse the conclusion that T is increasing in s. However, this can only occur if $\alpha'(T)$ is sufficiently large.

$W_{\beta s}$ has the same sign as $V_{\beta s}$; from (19) and the expressions for each of the terms in V we find

$$V_{\beta s} = e^{-\delta T} R(T) \left[1 - \frac{\kappa}{\delta + \kappa} \right] > 0$$

Together with $\beta'(T) > 0$ this strengthens our conclusion that T is increasing in s.

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