Exhibit 3

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TECHNICAL ADVANCE

# The outcome is in the assumptions: analyzing the effects on atmospheric $CO_2$ levels of increased use of bioenergy from forest biomass

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## Abstract

Recently, several studies have quantified the effects on atmospheric $CO_2$ concentration of an increased harvest level in forests. Although these studies agreed in their estimates of forest productivity, their conclusions were contradictory. This study tested the effect of four assumptions by which those papers differed. These assumptions regard (1) whether a single or a set of repeated harvests were considered, (2) at what stage in stand growth harvest takes place, (3) how the baseline is constructed, and (4) whether a carbon-cycle model is applied. A main finding was that current and future increase in the use of bioenergy should be studied considering a series of repeated harvests. Moreover, the time of harvest should be determined based on economical principles, thus taking place before stand growth culminates, which has implications for the design of the baseline scenario. When the most realistic assumptions are used and a carbon-cycle model is applied, an increased harvest level in forests leads to a permanent increase in atmospheric $CO_2$ concentration.

*Keywords:* atmosphere, bioenergy, carbon, climate change, Faustmann, impulse response functions

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## Introduction

The literature draws attention to the fact that the conversion of natural habitats to cropland leads to release of carbon, thus creating a biofuel carbon debt with a potential payback period of several decades or even centuries (see, for example, Gurgel *et al.*, 2007; Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Melillo *et al.*, 2009; Gibbs *et al.*, 2010; Lapola *et al.*, 2010).

The articles mentioned, however, studied biofuels based on fast-growing crops, in which the biomass harvested within 1 year is replaced by a new crop. In that case, the $CO_2$ released by combustion of the biomass could, for practical purposes, be ignored because the growth of the new crop requires the capture of the same amount of $CO_2$ within 1 year.

The issue becomes more complex if the source of bioenergy is a forest. The rotation period of a boreal forest stand is usually 70–120 years. Hence, a century might be required for the regrowth of a harvested boreal forest stand and recapture of the amount of $CO_2$ released originally. Despite this considerable time lag, recent studies have considered wood fuels from boreal forests as being carbon neutral, thus ignoring the amount of $CO_2$ released by the combustion of that wood (see, for example, Bright & Strømman, 2009; Sjølie *et al.*, 2010).

Keeping in mind that the carbon intensity of wood fuels is approximately at the level of coal, it is obvious that, from a methodological perspective, ignoring these emissions is not satisfactory. A body of literature has thus emerged that accounts for the amount of $CO_2$ released from combustion of biomass from forests and other slow-growing sources of biomass (see, for example, Manomet Center for Conservation Sciences, 2010; Cherubini *et al.*, 2011a,b; McKechnie *et al.*, 2011; Holtsmark, 2012).[1]

The conclusions of the articles mentioned vary significantly. For example, Holtsmark (2012) found that increasing the harvest of a forest permanently lowered the carbon stock of the forest and, consequently, permanently heightened the amount of $CO_2$ in the atmosphere. In contrast, Cherubini *et al.* (2011a,b) found that the $CO_2$ concentration in the atmosphere was *lower* 60–70 years after harvesting a relatively slow-growing forest than if the forest had not been harvested. Figure 1 illustrates these differences. The dashed line (left axis) depicts the atmospheric $CO_2$ that remains after harvest and combustion of a stock of biomass containing one metric ton of

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[1] Haberl *et al.* (2012a,b) and Schulze *et al.* (2012) include further references and discuss the implications of this literature.

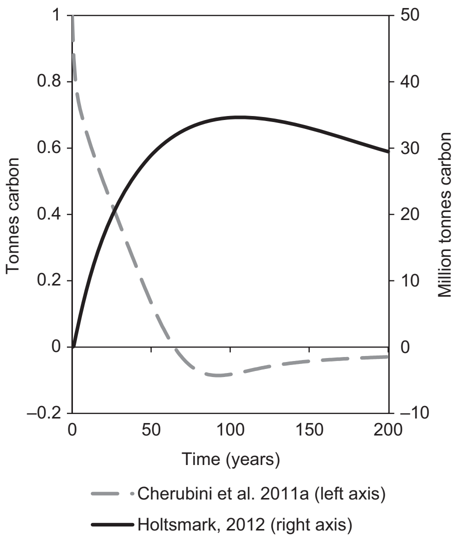

**Fig. 1** The dashed line (left axis) shows the atmospheric carbon that remains at time $t$ after a single harvest event at time $t = 0$, according to Cherubini *et al.* (2011a). The solid line (right axis) shows the atmospheric carbon that remains after a series of subsequent harvest events as a result of the application of an impulse response function to the results of Holtsmark (2012).

carbon, as found by Cherubini *et al.* (2011a). The solid line (right axis) shows the corresponding result in the work of Holtsmark (2012), in which increased harvest levels were predicted to increase the amount of $CO_2$ in the atmosphere in the long term.[2]

The different conclusions reached in these papers are explained by different methodological choices or assumptions. Therefore, an analysis of the importance of different simplifications and methodological choices is needed. Here, I will focus on four methodological choices.

1 Some studies consider a single harvest event occurring at the present time, with no biomass to be harvested in the future. However, a single harvest event performed at the present time will not produce any biomass in the future and is, therefore, not satisfactory if one wants to gather knowledge related to the consequences of the increased use of biomass presently *and* in the future. A single harvest event performed at the present time will not produce the required biomass if one aims to replace fossil fuels with biomass on a permanent basis. I will, therefore, demonstrate the effects of the replacement of a single harvest approach with a permanently increased harvest approach.

2 In some studies, it is assumed that a rotation period ends when the growth of the trees has culminated. Other studies take into account that, since the publication of the work of Faustmann (1849), and even earlier,[3], forest economists have known that a commercial forester will not postpone harvest until the growth of the trees has culminated, but will usually harvest at an earlier stage, following the so-called Faustmann rule. I will demonstrate the effects of the application of a rotation-period length that is in accordance with this rule.

3 Taking into account that harvest usually takes place in stands that are still growing, the baseline scenario becomes important. Not all studies take into account that the harvest scenario should be measured against a baseline scenario (with no harvest) in which the trees are still growing, thus capturing $CO_2$ from the atmosphere. I will demonstrate the importance of the use of a realistic baseline scenario along these lines.

4 In some studies, it is assumed, for simplicity, that the $CO_2$ released from the combustion of biomass accumulates and remains in the atmosphere forever. In other studies, an impulse response function is applied that models the ability of the ocean and of the terrestrial biosphere to absorb $CO_2$ from the atmosphere.

Table 1 provides an overview of how the five studies on the bioenergy from forests mentioned deal with these methodological choices. The approach of Cherubini *et al.* (2011a,b) was the inclusion of an impulse response function in the analysis, whereas the other studies listed applied a simple accumulation of $CO_2$. However, Cherubini *et al.* (2011a,b) and Manomet Center for Conservation Sciences (2010) considered a single harvest event exclusively. The methodology used for the construction of the baseline scenarios also varied.

To demonstrate quantitatively how the methodological choices influence the conclusions of this type of study, I will use the articles of Cherubini *et al.* (2011a) and Holtsmark (2012) as the starting point, adjust their methodological choices, and demonstrate the consequences of these adjustments. In contrast with the approach of Cherubini *et al.* (2011a), Holtsmark (2012) considered the consequences of permanently increasing harvest levels by studying a series of harvests. Moreover, Holtsmark (2012) took into account that the harvest usually takes place before the growth of the stand culminates and how the baseline scenario then should be designed. Holtsmark (2012), however, ignored the decay functions of atmospheric $CO_2$ and considered, for simplicity, accumulated emissions exclusively.

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[2] See the red curve in Fig. 4, page 423, in Holtsmark (2012). To achieve the somewhat different solid line in Fig. 1 here, the impulse response function of the Bern 2.5CC carbon-cycle model was applied; see Eqn (1).

[3] See the discussion of early contributions to this issue in Samuelson (1976) and Scorgie & Kennedy (1996).

**Table 1** Methodological differences in five recent papers dealing with bioenergy from forest biomass

| | Cherubini *et al.* (2011a) | Cherubini *et al.* (2011b) | Manomet Center for Conservation Sciences (2010) | McKechnie *et al.* (2011) | Holtsmark (2012) |
|---|---|---|---|---|---|
| Single harvest event or permanently higher harvest level? | Single | Single | Single | Permanent | Permanent |
| Does the no harvest baseline take growth and carbon capture in mature stands into account? | No | No | Yes | Yes | Yes |
| Is the time of harvest in accordance with the Faustmann rule? | No | Some of the scenarios | Yes | Yes | Yes |
| Impulse response function (IRF) or simple accumulation of $CO_2$? | IRF | IRF | Simple accumulation | Simple accumulation | Simple accumulation |

This study builds a bridge between the approaches of these two studies by taking atmospheric decay functions into account, as in Cherubini *et al.* (2011a), and including the realistic baseline scenario and the multiple harvest approach of Holtsmark (2012) in the analysis.

This paper is organized as follows. The model and the basic methodological choices are presented in the next section, the results are presented in the third section, and the results are discussed in the fourth section, which also includes the conclusions of the study.

## Materials and methods

Based on Forster *et al.* (2007) and the Bern 2.5CC carbon-cycle model, which those authors recommend, Cherubini *et al.* (2011a) applied the following atmospheric $CO_2$ decay function:

$$y(t) = \Delta_0 + \sum_{i=1}^{3} \Delta_i e^{(-t/\alpha_i)}, \tag{1}$$

where $y(t)$ represents the fraction of an initial pulse of $CO_2$ at time $t = 0$ that remains in the atmosphere at time $t$ and where $\alpha$ and $\Delta_i$ are parameters (Table 2). The time unit is 1 year. The decay is caused by the uptake of $CO_2$ by the ocean and by the terrestrial biosphere. Cherubini *et al.* (2011a) considered two cases. In the first case, those authors did not take into account the oceanic absorption of anthropogenic $CO_2$ from the atmosphere, although they considered this effect in the second case. For the purpose of this study, only the latter case is considered, as it is the most realistic and, therefore, the most interesting case.

It is assumed that the harvesting of biomass from forests is followed by replanting and the growth of new biomass. Regrowth implies carbon capture from the atmosphere. Cherubini *et al.* (2011a) assumed that the growth and carbon capture of the stand after a harvest follow the analytic form:

$$g(\tau) = \left(2\pi\sigma^2\right)^{1/2} e^{-(\tau-\mu)^2/2\sigma^2}, \tag{2}$$

**Table 2** Parameter values

| | | | Cherubini *et al.* (their case with $r = 100$) | Present case |
|---|---|---|---|---|
| $\Delta_0$ | 0.217 | $\sigma$ | 25 | 37.5 |
| $\Delta_1$ | 0.259 | $\mu$ | 50 | 75 |
| $\Delta_2$ | 0.338 | | | |
| $\Delta_3$ | 0.186 | | | |
| $\alpha_1$ | 172.9 | | | |
| $\alpha_2$ | 18.51 | | | |
| $\alpha_3$ | 1.186 | | | |

where $\sigma$ and $\mu$ are parameters and $\tau$ is the age of the stand. It can be deduced that a parcel with a stand age $\tau$ has the following carbon stock.[4]

$$C(\tau) = \left(2\pi\sigma^2\right)^{1/2} \sum_{\tau'=0}^{\tau} e^{-(\tau'-\mu)^2/2\sigma^2}. \tag{3}$$

The carbon captured by biomass regrowth should be considered in terms of negative emissions. Negative emissions should be treated symmetrically regarding positive emissions. Thus, the decay function presented in (1) should be applied to these negative emissions exactly as it is applied to the positive emissions.

Consider, for example, a parcel replanted at time $t = 0$. The carbon captured at time $t_1$ would be $g(t_1)$, and at time $t_2$, i.e., $t_2-t_1$ periods later, a fraction $y(t_2-t_1)$ of these negative emissions, i.e., $-g(t_1)\cdot y(t_2-t_1)$, is remaining in the atmosphere.

Assume now that, at time $t = 0$, the age of the stand is $\tau_m$ and that harvesting proceeds at this time. Combustion of the extracted biomass causes a $CO_2$ emission pulse $C(\tau_m)$, which, for simplicity, is labeled as C in the following equation. Taking the regrowth function described in (2) into account, the amount of $CO_2$ in the atmosphere $A_H(t)$ at time $t$, will be as follows:

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[4] To show exactly how the numerical examples in the next section are constructed, I used discrete time in the theoretical model description as well.

$$A_H(t) = C \cdot y(t) - \sum_{t'=0}^{t} g(t')y(t-t'), \tag{4}$$

where the first term on the right-hand side represents what is left of the pulse in the atmosphere at $t$ periods after harvesting, whereas the second term represents the effect of regrowth.

Thus far, I have followed the example of Cherubini *et al.* (2011a). However, the alternative to harvesting and combustion of biomass is to not harvest: i.e., letting the stand grow and capture more $CO_2$. In this case, the amount of $CO_2$ in the atmosphere would evolve as follows.

$$A_{\mathrm{NH}}(t) = -\sum_{t'=0}^{t} \mathrm{g}(\tau_{\mathrm{m}} + t')\mathrm{y}(t-t'). \tag{5}$$

Note the assumption of Cherubini *et al.* (2011a) that harvesting always takes place when the growth of the stand has culminated [see (c) in Fig. 2], which is the reason why those authors disregarded this effect. If we take this effect into account, the net effect of harvesting on the atmospheric carbon content will be as follows:

$$A_{\mathrm{S}}(t) = A_{\mathrm{H}}(t) - A_{\mathrm{NH}}(t). \tag{6}$$

The time at which harvesting takes place is a pertinent point. If we assume that the stock of trunks in the stand is proportional to the amount of biomass $C(t)$ and that the market interest rate is $r$, then, according to the Faustmann rule, a forest owner will harvest when the stand age $\tau$ satisfies the following equation.

$$\frac{C'(\tau)}{C(\tau)} = \frac{r}{1 - e^{-r\tau}}. \tag{7}$$

As the interest rate approaches zero, (7) is reduced to

$$\frac{C'(\tau)}{C(\tau)} = \frac{1}{\tau}. \tag{8}$$

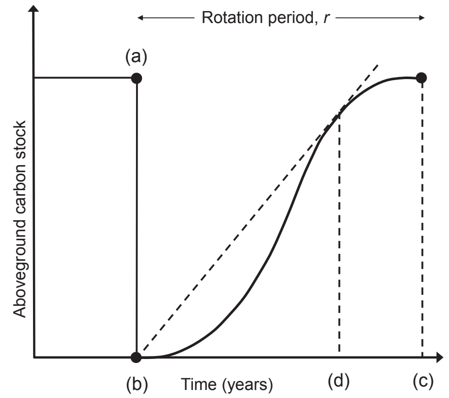

**Fig. 2** This diagram is identical to Fig. 1 in Cherubini *et al.* (2011a), with the exception of the addition of the dashed lines. Cherubini *et al.* (2011a) assumed that harvest takes place at (c), whereas the Faustmann rule says that harvest usually will take place somewhere between (b) and (d).

Harvesting at a time at which $\tau$ satisfies (8) implies a maximum sustained yield (MSY) and harvesting at point (d) in Fig. 2. To the extent that the forest owner discounts future income, the rotation period will be shorter.

The intuition behind the Faustmann rule is as follows. The forest owner takes into consideration his opportunity to invest the harvest profit, creating postharvest periodic revenue of $rC(\tau)$. Postponing the harvest has an alternative cost corresponding to this revenue. This could easily be interpreted as that harvest should take place when $\tau$ satisfies the equation $C(\tau) = rC'(\tau)$. However, the Faustmann rule (7) also takes into account that, if the first harvest is postponed, all future harvests must also be postponed. This leads to Eqn (7), which implies an even earlier harvest than is indicated by the more simple equation $C(\tau) = rC'(\tau)$.

The application of the limiting case of the Faustmann rule described in (8) to the slower growing forest studied by Cherubini *et al.* (2011a), i.e., a forest with a rotation span of 100 years, implies that harvesting occurs when the stand is 70 years old. In other words, the slower growing forest considered by Cherubini *et al.* (2011a) is actually a relatively rapidly growing boreal forest. The rotation period for MSY in most Scandinavian forests is reportedly 70–120 years.

I shall, therefore, adjust the parametric assumptions to allow for a MSY rotation period of 100 years for the stand in question. I will accomplish this using the parameters $\sigma = 37.5$ and $\mu = 75$ (Table 2). Given these assumptions, the growth and carbon capture of the stand will culminate at a stand age of approximately 150 years. In other words, the stand will continue to grow and capture $CO_2$ from the atmosphere, as specified in Eqn (5), if it is not harvested after reaching maturity. The two compared (re)growth scenarios are shown in Fig. 3. The solid line traces the carbon stock of the stand if it is harvested at time $t = 0$, whereas the dashed line traces the carbon stock of the stand if its age is 100 years at time $t = 0$ and if it is not harvested.

## Results

### *Single harvest event*

First, consider the case studied by Cherubini *et al.* (2011a), with a rotation period of 100 years. The harvest gives rise to a pulse emission of one metric ton of carbon at time 0, which is recaptured completely by the regrowth of the stand over the next 100 years. After these 100 years, there is no further growth on the stand. The dashed line in Fig. 4 shows the atmospheric carbon remaining from this pulse, according to the calculations of those authors. Note that, after ca. 65 years, a lower carbon concentration in the atmosphere is estimated in the presence of a harvest event compared with the case without harvest. This is so because increased atmospheric $CO_2$ levels lead to an increase in the accumulation of carbon in the terrestrial ecosystems, as well as to an increase in oceanic $CO_2$ absorption.

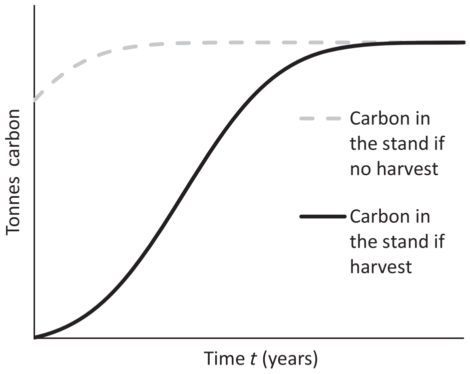

**Fig. 3** Development of the carbon stock of a stand that is mature at time 0. The solid line represents the harvest case. The dashed line represents the no-harvest case.

As argued in the previous section, when dealing with a boreal forest, it would be appropriate to consider a MSY rotation period of 100 years and culmination of growth after approximately 150 years, which would be consistent both with the Faustmann rule and with a typical boreal forest stand. The harvest of this forest stand at time 0 is assumed to lead to a pulse of emission of one ton of carbon. The gray, solid line in Fig. 4 shows the level of atmospheric carbon from the pulse that remains in this case; cf. Eqn (4).

The question of the use of an appropriate baseline arises at this point. As Cherubini *et al.* (2011a) assumed that there is no further growth on the stand in the no-harvest case, there is no change in atmospheric carbon in their baseline scenario. The scenario is different if it is assumed that there is continued growth in the no-harvest case. The dotted curve in Fig. 4 traces the effect on atmospheric $CO_2$ levels in the no-harvest case and corresponds to Eqn (5). This curve dips below zero because there is no emission pulse at time $t = 0$, although carbon is still captured by continued growth after this time point.

Our interest is related to the *net* effect of harvesting on atmospheric $CO_2$ levels. This can be computed by subtracting the amount of atmospheric carbon in the no-harvest case from the amount of atmospheric carbon in the case with harvest; cf. Eqn (6). The result is the double-line curve in Fig. 4. Compared with the case studied by Cherubini *et al.* (2011a), this case gives a somewhat longer period of enhanced levels of atmospheric $CO_2$.

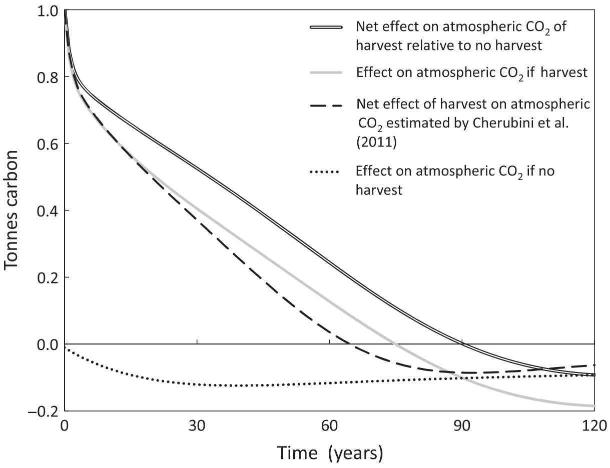

**Fig. 4** The dashed line depicts the remaining atmospheric carbon for the methodology applied by Cherubini *et al.* (2011a), with a rotation period of 100 years. The gray, solid line represents the atmospheric carbon remaining with a slower growing stand with harvesting occurring at a stand age of 100 years. In both cases, harvesting of this stand at time 0 is assumed to cause an emission pulse of one ton of carbon. The dotted curve traces the effect on atmospheric carbon levels in the no-harvest case, whereas the double-line curve shows the net effect of harvest compared with no harvest.

### *Multiple harvest events*

The numerical examples presented in the previous section measure the effect of a *single harvest event.* However, IPCC documents, such as Chum *et al.* (2012), envisage a permanent increase in the use of bioenergy and, accordingly, a higher harvest rate. Therefore, in the following paragraphs, I will consider a case in which the harvest events described in the previous section take place every year on a permanent basis.

Consider now a forest with an age structure such that every year one parcel, each with a growth function described by Eqns (1) and (2), reaches the stand age $\tau_m$ and is, therefore, considered mature and ready for harvest. The net effect on atmospheric carbon of harvesting a stand every year compared with the case where the parcels are left unharvested, is given by the following equation.

$$A(t) = \sum_{t'=0}^{t} A_S(t'). \tag{9}$$

The function $A_S(t)$ is defined in Eqn (6). Given the numerical assumptions, the expression is shown by the solid line depicted in Fig. 5. Other than the difference in scale (million tons and tons of carbon), the solid line shown in Fig. 5 is not far off the corresponding result that is obtained when the impulse response function is applied to the data of Holtsmark (2012), which is indicated by the dotted curve shown in Fig. 5.

To have intuition to the above described results, study the dashed curve shown in Fig. 5, which is identical to the double lined curve depicted in Fig. 4. These curves show that the effect of a single harvest on atmospheric $CO_2$ levels is a two-stage process. During the first stage, the level of atmospheric $CO_2$ is higher than it would have been in the absence of harvest, whereas the reverse is true in the second stage. The observation

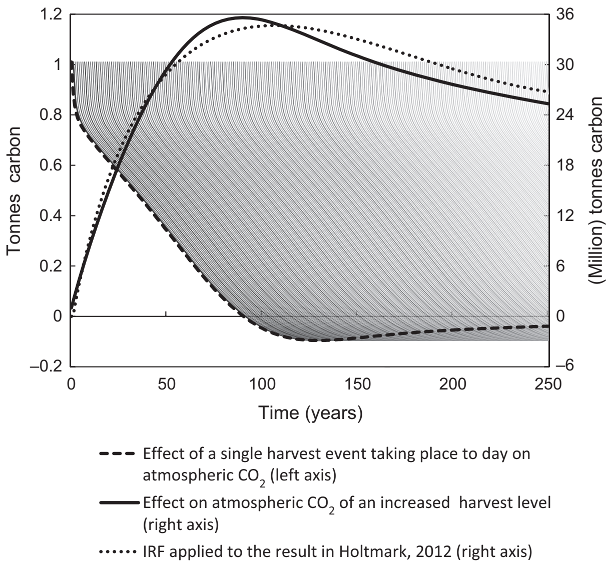

**Fig. 5** The dashed curve (left axis) shows the net effect on atmospheric carbon of a single harvest event taking place today compared with the no-harvest case. The set of thin curves depicts similar net effects of subsequent annual harvest events. The thick solid line (right axis) shows the total net atmospheric carbon that remains after this series of identical annual harvest events. The dotted curve (right axis) represents the effect of an increased harvest level, as described in Holtsmark (2012).

that the negative effect in the second stage is smaller than the positive effect during the first stage is important to predict the outcome of a series of harvest events.

Next, consider the case in which harvest takes place annually. Every year, there is a pulse of emissions of 1 ton of carbon with subsequent regrowth on the stand. The set of thin curves shown in Fig. 5 represent the effects of these subsequent annual harvest events. The net effect on atmospheric $CO_2$ of this series of harvest events is calculated via vertical summation of this set of curves and the dashed curve. This gives the solid line depicted in Fig. 5, which is measured on the right axis.

Note that the dashed curve converges toward zero, whereas the solid line converges toward 19 tons of carbon (result not shown here). Hence, a single harvest event has no long-term effect on atmospheric carbon, whereas a permanently increased harvest level will increase atmospheric $CO_2$ permanently. It follows that an increased harvest level is not a carbon-neutral activity not even in the long term, whereas a single harvest event is a carbon-neutral activity in the long term.

## Discussion

The realization that wood fuels are not carbon neutral gives rise to a number of methodological questions or assumptions regarding the manner via which $CO_2$ emissions from wood fuels should be modeled. In this study, I have focused on four methodological choices. First, I analyzed whether the consideration of a single harvest event is sufficient when the consequences of the increased use of biomass presently and in the future are to be analyzed. Second, I analyzed whether the assumption that the rotation period ends when the growth of the trees has culminated is satisfactory. Third, I analyzed the manner via which the baseline no-harvest scenario should be constructed. Finally, I studied the importance of including impulse response functions in the analyses.

The work of Cherubini *et al.* (2011a) was used as a starting point to evaluate the importance of these methodological choices. The approach of those authors of using an impulse response function was adopted. However, their model was adjusted taking into account that harvest usually takes place before the growth of the trees has culminated. The baseline (no harvest) scenario was adjusted accordingly. Finally, a single harvest approach was supplemented with a multiharvest approach, which reflects the fact that the policy proposal to be analyzed addresses the question of whether biomass should be harvested at the current time *and* in the future.

The numerical simulations provided information on the importance of these methodological choices. First, they showed that the results change fundamentally when a single harvest approach is replaced with a multiharvest approach reflecting a permanently increased harvest level. A single harvest approach could lead to the conclusion that wood fuels are carbon neutral in the long term, but not in the short term, whereas a multiharvest approach leads to the conclusion that wood fuels are not carbon neutral, neither in the long term nor in the short term. The multiharvest approach revealed that a permanently increased harvest level leads to a permanent increase in atmospheric carbon also when a realistic carbon-cycle model is taken into account.

Second, it was found that the consideration that harvest usually takes place before growth of the trees has culminated and the consequent adjustment of the baseline have a significant effect on the results, although they are not changed fundamentally.

Third, the results of Holtsmark (2012) were adjusted by incorporating an impulse response function in the analyses. This approach did not change the results fundamentally. Using simple accumulation of $CO_2$ in the atmosphere in this type of study is an approximation that is acceptable.

Another question, which was not discussed here, concerns the extent to which the increased harvest of a forest may reduce atmospheric carbon if the extracted biomass replaces fossil energy sources. For a discussion of this question, see Holtsmark (2012) and McKechnie *et al.* (2011).

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## References

Bright RM, Strømman AH (2009) Life cycle assessment of second generation bioethanol produced from Scandinavian boreal forest resources. *Journal of Industrial Ecology*, **13**, 514–530.

Cherubini F, Peters GP, Berntsen T, Strømman AH, Hertwich E (2011a) $CO_2$ emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *Global Change Biology Bioenergy*, **3**, 413–426.

Cherubini F, Strømman AH, Hertwich E (2011b) Effects of boreal forest management practices on the climate impact of $CO_2$ emissions from bioenergy. *Ecological Modelling*, **223**, 59–66.

Chum H, Faaij A, Moreira J (eds) *et al.* (2012) *Bioenergy*. Cambridge University Press, Cambridge, UK.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Faustmann M (1849) Berechnung des Werthes, weichen Waldboden sowie nach nicht haubare Holzbestande für de Weltwirtschaft besitzen. *Allgemeine Forst und Jagd Zeitung*, **25**, 441.

Forster P, Ramaswamy V, Artaxo P *et al.* (2007) Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (ed. Solomon S). Intergovernmental Panel on Climate Change, Cambridge, UK.

Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings from the National Academy of Sciences*, **107**, 16732–16737.

Gurgel AJ, Reilly M, Paltsev S (2007) Potential land use implications of a global biofuels industry. *Journal of Agricultural & Food Industrial Organization*, **5**, 1–34.

Haberl H, Sprinz D, Bonazountas M *et al.* (2012a) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, **45**, 18–23.

Haberl H, Schulze ED, Körner C, Law BE, Holtsmark B, Luyssaert S (2012b) Response: complexities of sustainable forest use. *GCB Bioenergy*, doi: 10.1111/gcbb.12004.

Holtsmark B (2012) Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, **112**, 415–428.

Lapola D, Schaldach MR, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings from the National Academy of Sciences*, **103**, 11206–11210.

Manomet Center for Conservation Sciences (2010) Massachusetts biomass sustainability and carbon policy study: report to the commonwealth of Massachusetts department of energy resources (ed. Walker T). Natural Capital Initiative Report NCI-2010-03. Brunswick, ME, USA.

McKechnie J, Colombo S, Chen J, Mabee W, Maclean HL (2011) Forest bioenergy of forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, **45**, 789–795.

Melillo JM, Reilly JM, Kicklighter DW *et al.* (2009) Indirect emissions from biofuels: how important? *Science*, **326**, 1397–1399.

Samuelson PA (1976) Economics of forestry in an evolving society. *Economic Inquiry*, **14**, 466–492.

Schulze ED, Körner C, Law BE, Haberl H, Luyssaert S (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, doi: 10.1111/j.17571707.2012.01169.x.

Scorgie M, Kennedy J (1996) Who discovered the Faustmann condition? *History of Political Economy*, **28**, 77–80.

Searchinger TD, Heimlich R, Houghton RA *et al.* (2008) Use of US croplands for biofuels increases greenhouse gas through emissions from land-use change. *Science*, **319**, 1238–1240.

Sjølie HK, Trømborg E, Solberg B, Bolkesjø TF (2010) Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. *Forest Policy and Economics*, **12**, 57–66.