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Optimal forest rotation under carbon pricing and forest damage risk

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Abstract

Forests have two notable economic roles in the future: providing renewable raw material and storing carbon to mitigate climate change. The pricing of forest carbon leads to longer rotation times and consequently larger carbon stocks, but also exposes landowners to a greater risk of forest damage. This paper investigates optimal forest rotation under carbon pricing and forest damage risk. I provide the first-order optimality conditions for this problem and illustrate the setting with numerical calculations representing boreal forests. Under the considered range of parametrizations, carbon price has far greater impact on the optimal rotation than the damage probability. Increasing forest carbon stocks through longer rotations is thus economically attractive option for mitigating climate change, despite the forest damage risk. Carbon pricing increases land expectation value and reduces the economic risks posed by disturbances. The production possibility frontier between harvests and carbon storage suggests that significantly larger forests carbon stocks are achievable, but implies lower harvests. However, forests' societally optimal role between these two activities is not yet clear-cut; but rests on the future development of relative prices between timber, carbon and other commodities dependent on land-use.

Keywords: Optimal forest rotation, climate change, carbon pricing, forest damage

1. Introduction

Meeting ambitious climatic goals – such as keeping temperature change within 1.5°C, as prescribed in the Paris Agreement – is likely to require

removing significant amounts of carbon dioxide from the atmosphere (Rogelj et al, 2018). This heightened challenge in climate change mitigation has prompted stronger interest in enhancing forest carbon sinks (see Sedjo and Sohngen, 2012, for a review). Due to the vast size of the forest ecosystems, large potential exists in both capturing and storing atmospheric carbon. Forests could, therefore, provide a significant contribution to the grand effort needed to mitigate climate change and meet the Paris Agreement targets (see e.g. Griscom et al, 2017; Favero et al, 2017).

While an extensive expansion of forest carbon stocks might be possible from the perspective of natural sciences, it is not evident that such would be economically optimal. In an ideal economic setting, all flows of carbon to and from forests should be priced with the social cost of carbon (Nordhaus, 1991). Policy that imposes a price for forest carbon – e.g. through subsidies and taxes for the landowner – would provide an efficient incentive to expand the forest carbon stock. This would generally lead to longer rotation times in managed forests (van Kooten et al, 1995) and expansion of forest area (Sohngen and Mendelsohn, 2003). Further, the effect is greatly amplified if the price of carbon increases over time, which is a common result from long-term economic assessments on optimal mitigation strategies (Ekholm, 2016).

By lengthening the rotation, however, the landowner is exposed to a higher risk that a fire, storm or other damage destroys the stand before the trees are harvested. It has been shown that the presence of a forest damage risk shortens the optimal rotation (Reed, 1984), although this analysis did not account for forest carbon pricing. By shortening the optimal rotation, the forest damage risk leads to lower forest carbon stocks and a lower potential for mitigating climate change.

Additional to the loss of harvestable wood, forest damages are detrimental towards the climatic aims. Damages disrupt forest growth, and therefore the trees' capability to drain atmospheric carbon; and release some of the stored carbon back to the air, particularly in the case of forest fires. These factors attenuate the impact a carbon pricing policy has on forest management. A further motivation for considering the damage risk is that climate change itself is likely to increase the risk level in the future.

For understanding how large a contribution forests might have towards mitigating climate change, were proper incentives put in place, it is of importance to analyze optimal rotation in the presence of carbon pricing and forest damage risk. This will answer which of the counteracting forces – car-

bon pricing lengthening and damage risk shortening the optimal rotation – dominates optimal forest management. The optimal rotation approach can illustrate how largely the damage risk might obviate the economic potential for forests to drain carbon, and also how the relative pricing between timber and carbon affects the supply of wood and mitigation. Further, one can also investigate how carbon pricing and the damage risk affect the returns and economic risks for the landowner.

This paper presents the first-order optimality conditions for forest rotation length under carbon pricing and forest damage risk. In essence, I combine the approaches of Reed (1984) for forest damage risk and van Kooten et al (1995) for carbon pricing. Using this model, I present optimal rotation length, land expected value, the risk in returns, and the production possibility frontier between carbon stocks and timber yield (Pingoud et al, 2018).

A number of authors have analyzed the relationship between carbon pricing and damage risk using numerical optimization methods. Stainback and Alavalapati (2004) optimize the land expected value directly in a relatively similar problem setting, while Couture and Reynaud (2011) and Daigneault et al (2010) used stochastic dynamic programming, taking respectively also thinnings and risk preferences into account.

The model I employ in this paper is closest to that of Stainback and Alavalapati (2004), but more general in terms of the stochastic process underlying forest damages, the pricing of timber harvested at different ages, and the carbon dynamics after a harvest or a damage event. Moreover, the recursive formulation used here allows presenting the model in a more compact form. The numerical examples portraying boreal forests involve more realistic representation of carbon retention in dead wood and products, with numerical estimates based on empirical literature. I also present results on unexplored aspects, such as the economic risk and the production possibility frontier between wood production and carbon storage.

2. Determining the optimal rotation length

The problem setting looks at a forest-owner, who aims to find the rotation length T that maximizes the expected net revenues from an infinite chain of rotations when starting from bare land. Future income and costs are discounted with rate r . Changes in carbon stocks are priced with a constant price P_c (in €/t $_{CO_2}$), which is externally set by a policy-maker, analogously to the approach of van Kooten et al (1995). The harvested timber from final

fellings has a value described by $P_f(T)$ (in €/m³), which depends on what age T the stand is harvested. The timber value $P_f(T)$ does not, however, cover the value of carbon stored in the harvested wood. The gradual release of carbon from harvest residues and wood products is priced with P_c .

At each point of time, the considered forest area is subject to a risk of forest damage. In case the forest damage occurs, some of the carbon stock can be released to the atmosphere, while some part of the wood can be salvaged and sold. As with harvest residues and wood products, the carbon released due to the disturbance is priced with P_c . New rotation begins after final fellings or damage, and incurs a regeneration cost R .

Let Z_1, Z_2, \dots be a sequence of random variables that represent the stand ages at which a damage event would occur for each subsequent rotation. If final fellings occur at age T , the n^{th} rotation ends in harvest if $T \leq Z_n$. Otherwise the damage destroys the stand and a new rotation follows.¹ Assume that the random variables are independent and identically distributed. Denote the probability density for $Z_n = t$ with $p(t)$. This approach is very similar to that of Reed (1984), but slightly more generic, allowing the probability to depend on the stand age. It is worth noting, however, that the stand age is merely a proxy for the evolution of the stand's physical characteristics, like density, that actually determine the risk.

To determine the land expectation value, let us first split the net revenue calculation from a single rotation into two mutually exclusive cases. $D(t)$ indicates net revenues if forest damage occurs at time t , with $t < T$:

$$D(t) = \alpha P_c \int_0^t e^{-r\tau} v'(\tau) d\tau - e^{-rt} ((1 - \gamma)\alpha P_c v(t) + R) \quad (1)$$

$H(T)$ indicates net revenue if no damage occurs, and final fellings take place at time T :

$$H(T) = \alpha P_c \int_0^T e^{-r\tau} v'(\tau) d\tau + e^{-rT} ((P_f(T) - (1 - \beta)\alpha P_c) v(T) - R) \quad (2)$$

In these equations, $v(t)$ denotes the stem volume at age t (in m³/ha)², α is the total carbon content of living biomass per stem volume (in t_{CO₂}/m³,

¹Xu et al (2016) have provided an extension that allows multiple disturbances in one rotation, whereby the stand is not lost completely in a damage event.

²All values are here given in SI or compatible units. t_C stands for tonnes of carbon and t_{CO_2} for tonne of carbon dioxide, which can be converted to each other using the ratio of molecular weights.

as P_c is given in terms of $\text{€}/t_{CO_2}$), while γ and β respectively represent the fractions of carbon that remain stored after forest damage and harvest. That is, the forest owner is required to pay for the fraction $(1 - \gamma)$ or $(1 - \beta)$ of the trees' carbon content.

The expressions $D(t)$ and $H(T)$ cover only a single rotation. The objective is, however, to maximize the expected net present value from an infinite chain of rotations. As the problem setting is identical for each rotation – prices and other parameters are assumed to remain constant over time – it is possible to use a recursive formulation.

Let $V(T)$ be a value function, portraying the expected net present value subject to the rotation length T . Then, the expected land value for rotation length T can be expressed as

$$V(T) = \int_0^T p(t) \left(D(t) + e^{-rt} V(T) \right) dt + \int_T^\infty p(t) \left(H(T) + e^{-rT} V(T) \right) dt \quad (3)$$

This formulation incorporates the expected value of subsequent rotations recursively through the expected land value $V(T)$, discounted to the start of the first rotation (see e.g. Susaeta et al, 2014). That is, after the first rotation ends – either in disturbance or harvest – the stand is again bare land, and thus has the value $V(T)$ under the assumption that rotation length T is used in subsequent rotations. Upon rearranging, $V(T)$ can be presented as a function of the optimal rotation length:

$$V(T) = \frac{\int_0^T D(t)p(t) dt + H(T) \int_T^\infty p(t) dt}{1 - \int_0^T p(t)e^{-rt} dt - e^{-rT} \int_T^\infty p(t) dt} \quad (4)$$

This formula resembles the expression for bare land value in a non-probabilistic setting – i.e. without the possibility of forest damage – only that the net revenues in the numerator and the recursion factor in the denominator are now calculated in the form of expected values. The first-order optimality conditions in this general setting could be stated by finding the rotation age T^* for which the derivative of the value function (4) is zero.

So far the damage probability $p(t)$ has been an arbitrary function conditional on the stand age. To present a more concrete case, the annual damage probability is assumed in the following to remain constant over the stand's lifetime. Consequently, the damages follow a Poisson process and occur at intervals that are exponentially distributed:

$$p(t) = \lambda e^{-\lambda t} \quad (5)$$

where λ denotes the average rate of forest damages per year.

Under this probability assumption, upon some algebraic manipulation on the first-order condition $V'(T^*) = 0$, one can arrive at the following expression

$$\begin{aligned}
& \left(\left(1 - e^{-(\lambda+r)T^*} \right) P'_f(T^*) - (\lambda + r)P_f(T^*) \right. \\
& \quad \left. - \alpha P_c \left(r(\beta - 1) + \lambda(\beta - \gamma) - \lambda(1 - \gamma)e^{-(\lambda+r)T^*} \right) \right) v(T^*) \\
& + \left(1 - e^{-(\lambda+r)T^*} \right) (\alpha\beta P_c + P_f(T^*)) v'(T^*) \\
& - \alpha P_c (\lambda + r) e^{-\lambda T^*} \int_0^{T^*} e^{-r\tau} v'(\tau) d\tau \\
& - (\lambda + r) \int_0^{T^*} \lambda e^{-\lambda t} \left(\alpha P_c \int_0^t e^{-r\tau} v'(\tau) d\tau - e^{-rt} (\alpha P_c (1 - \gamma) v(t) + R) \right) dt \\
& + \left(r + \lambda e^{-(\lambda+r)T^*} \right) R = 0,
\end{aligned} \tag{6}$$

which makes it possible to solve the optimal rotation length T^* numerically. With a suitable choice of the functional form for $v'(\tau)$ – as is done in section 3 – the integrals of (6) can be solved, yielding an analytic expression for the first-order condition.

As the problem setting is a generalization from the problem settings of both Reed (1984) and van Kooten et al (1995), equation (6) simplifies to the optimality conditions of these cases with appropriate parameters. Setting $P_c = 0$ eliminates carbon pricing, and with a constant timber price $P_f(T) = P_f$ the equation (6) simplifies to the first-order conditions proposed by Reed (1984). Similarly, setting $\lambda = 0$, $R = 0$ and $P_f(T) = P_f$ eliminates the damage risk and regeneration costs, making (6) correspond the formula presented by van Kooten et al (1995). Substitutions $P_c = 0$, $P_f(T) = P_f$ and $\lambda = 0$ together simplify (6) to the first-order condition of the Faustmann problem.

Last, one should note that the parameters γ and β provide considerable flexibility in determining the carbon costs due to damage or harvest, respectively. In the numerical examples of Section 3, I assume that carbon is released gradually to the atmosphere after harvest or a damage event, and that this gradual decay is priced with P_c . The net present value of this can be represented as a cost to the forest owner during the harvest or damage through β and γ . Although in the case of harvests, these costs would be borne by some other actor in the economy, efficient markets would pass this

cost to the price of timber, and this affects the forest-owners decision-making. As $P_f(t)$ was assumed to exclude the value of carbon embodied in the sold timber, this lower price due to the carbon cost can be captured through β .

Moreover, γ can be used to represent that a fraction δ of the timber value can be salvaged and sold after a damage event, including the salvage cost and lower value of the salvaged wood. Assume that a fraction $\tilde{\gamma}$ of the carbon is stored after damage. Then, one can write $\gamma = \tilde{\gamma} + \frac{\delta P_f}{\alpha P_c}$. By inserting this into (1), one arrives at two terms representing the carbon costs and salvage value after a damage event. One can also set $\gamma = 1$ if no payments are required for the carbon release from forest damage.

3. Numerical cases

To illustrate, I calculate the optimal rotation for Scots pine and Norway spruce stands in Southern Finland under a range of carbon prices and damage risks. The calculated cases depart from reality in that the problem formulation omits thinnings, although they are a common practice in Finnish forest management; but nevertheless provide insights into the effects of carbon pricing and damage risks on optimal rotation in boreal forests. The interested reader can refer to e.g. Pohjola and Valsta (2007) for an analysis with carbon pricing and thinnings.

3.1. Setup

The stem volume is presented in Figure 1 as a function of stand age. The functional representation is determined through $v'(t) = v_1 t e^{v_2 t} + v_3 t^3 e^{v_4 t}$, which allows flexible fit and a closed-form solution for both $v(t)$ and when integrating $e^{-rt} v'(t)$, as is done in (6). Additionally, the volume $v(t)$ includes a constant term v_5 , which sets $v(0) = 0$. The parameter values are given in Table 1. The conversion from stem volume to total carbon content (α), is from Lehtonen et al (2004), assuming a 50% carbon content of biomass. The discount rate is fixed at 3% and regeneration cost at zero.

The price of timber depends on the stand age, reflecting that younger stands yield more low-price pulpwood and older stands heavier logs that are priced higher. The price is assumed to increase from zero to $P_{f,max} = 60 \text{ €/m}^3$, according to $P_f(t) = (\mu t)^2 e^{\mu t} / (1 + (\mu t)^2 e^{\mu t}) P_{f,max}$, where $\mu = 0.015$. This parametrisation is based loosely on energy wood, pulpwood and sawlog prices in Southern Finland during the last 10 years, and used for illustrative purposes. It should be noted that other timber prices would yield the same

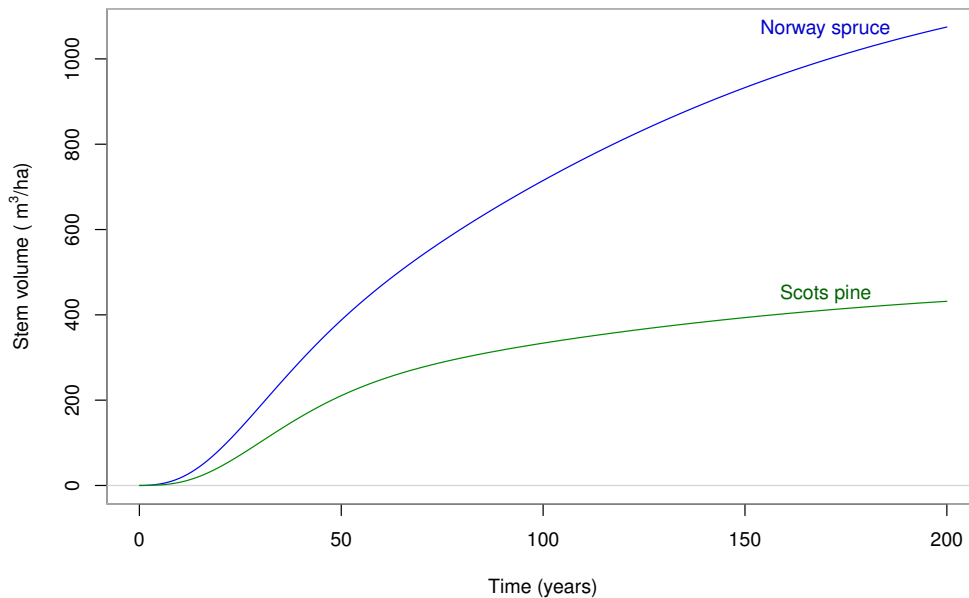


Figure 1: Stem volume as a function of stand age $v(t)$ for illustrative Scots pine and Norway spruce stands in Southern Finland.

optimal rotation lengths as calculated here if the carbon price P_c and regeneration costs R are scaled proportionally to the change in $P_f(t)$.

The parameters γ and β are used to portray the net present value of carbon payments from a gradual decay of carbon stocks following damage or harvest. That is, after disturbance and harvest, the wood biomass is assumed to enter various product pools, e.g. harvest residues or long-term wood products; which decay with different rates and release the carbon into the atmosphere. Consistent with the premise of pricing all carbon flows with the same carbon price P_c , the values of γ and β are set so that the terms $(1 - \gamma)\alpha P_c$ and $(1 - \beta)\alpha P_c$ in equations (1) and (2) represent the discounted value of carbon payments due to the carbon stock lost in future years. Although the forest-owner would not probably own the decaying carbon stocks after harvest, it is assumed that the market price of harvested wood would be lowered from $P_f(t)$ by $(1 - \beta)\alpha P_c$ due to the liability of paying for the future carbon release.

I consider here two types of forest damage: storm and fire. Carbon is released with differing dynamics during and after a storm or forest fire, for

which I provide estimates based on earlier empirical research. Analogous estimates are made for carbon retention if the trees are felled for long-lived wood products. The approach could be parametrized for other damages, e.g. insect infestations, in subsequent research.

The shares of carbon stored in different tree compartments – roots, stem, branches and foliage – are from Lehtonen et al (2004) and their decay rates from Repo et al (2011). The soil carbon stock due to natural litter production and decay is not considered here. After a storm, the whole tree biomass is assumed to be left on site. The stem and stump are assumed to decay with the rate of 20 cm stumps in Repo et al (2011), the branches with 2 cm diameter rate, and the foliage rapidly. For fire, based on Liski et al (1998), I assume that 100% of needles, 75% of branches and 25% of stemwood is burnt; with the remaining fraction decaying as above.

For harvested wood products, I assume the wood is used in sawmills and ends up in construction, using numbers from Pingoud et al (2001). From the stemwood carbon stock, 56% is released at the sawmill; and of the remaining fraction, 50% ends up in long timeframe and 15% in medium timeframe products, the rest being released. Harvest residues are assumed to remain on site and to decay as above.

The resulting carbon stock dynamics are presented in Figure 2. The values of γ and β – when discounted with a 3% rate – are presented in Table 1.

Two parameters for which it is harder to provide reliable estimates are the carbon price and damage probability. A recent sensitivity analysis regarding factors underpinning the social cost of carbon found a range from 10 $\$/t_{CO_2}$ to 300 $\$/t_{CO_2}$ defensible (Ekholm, 2018). With a discount rate of 3%, which is same as used here, the carbon price range extends to slightly over 100 $\$/t_{CO_2}$.

While statistics on the historical frequency of forest damages do exist, they do not reflect the future risk level in a warmer climate. To have some point of reference, nevertheless, one could look at the exceptionally vast wildfires in Sweden during summer 2018. A result of a heatwave throughout the Northern Hemisphere, reported 25 000 hectares of forests were affected. While extensive, the affected area corresponds to only 0.1% of Sweden’s productive forest area. Lehtonen et al (2016) estimated that the number of fires in Finland could almost double within the century under moderate climate change. The risk is yet highly dependent on local conditions, and far higher damage probabilities have been presented for temperate forests (e.g. Stainback and Alavalapati, 2004). Nevertheless, climate change is projected

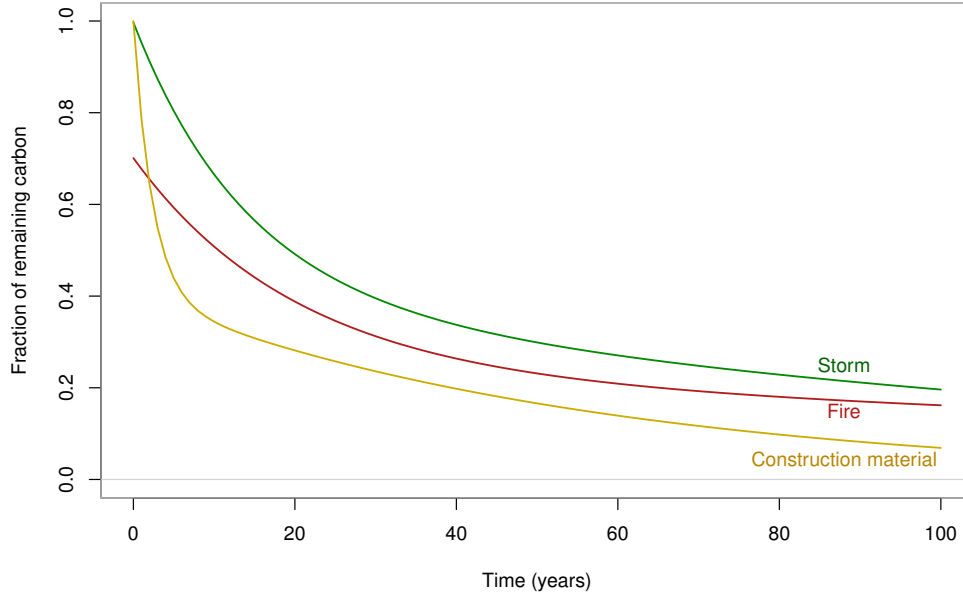


Figure 2: The dynamics of carbon stock remaining after a storm, fire or harvest for sawmill products.

to increase particularly the fire risks throughout the planet (Seidl et al, 2017).

Based on these considerations, I calculate the results for a range of carbon prices P_c and annual probabilities of damage λ , from 0 to 100 €/t $_{CO_2}$ and 0% to 1% respectively.

3.2. Optimal rotation length

Optimal rotation lengths are presented in Figure 3 for Scots pine and Norway spruce under the considered range of carbon prices and damage probabilities, separately for fire and storm damage. Carbon pricing lengthens the optimal rotation considerably. The effect is more pronounced for spruce, which retains its capacity for draining atmospheric carbon longer than pine. With high carbon price and low or moderate damage probability, the optimal rotation length can extend to infinity. In such case, despite the declining annual growth rate, the expected net present value from forthcoming carbon sequestration remains higher than the sum of values from bare land and sold timber minus the discounted value of lost carbon stocks.

Table 1: Species-specific parameter values for the illustrative calculations. Carbon content α is presented in terms of t_{CO_2}/m^3 instead of elemental carbon, to be consistent with the carbon price given in $\text{€}/t_{CO_2}$. The parameter v_5 is a constant term in the function $v(t)$.

		Scots pine	Norway spruce
Carbon content per stem volume	α (t_{CO_2}/m^3)	1.29	1.36
Carbon stored after fire	γ_{fire}	0.403	0.387
Carbon stored after storm	γ_{storm}	0.525	0.508
Carbon stored after harvest	β	0.319	0.303
Stem volume parameters:	v_1	0.0632	0.235
	v_2	-0.0153	-0.0153
	v_3	0.00414	0.00621
	v_4	-0.104	-0.109
	v_5	-483	-1270

A higher damage probability shortens the optimal rotation length, but its impact is far more limited compared to the carbon price. Even with the highest considered levels of forest damage probability, the optimal rotations lengthen notably with higher carbon price.

The correspondence between damage probability and carbon price towards the optimal rotation length is relatively linear with the parameters used in Figure 3. The storm and fire cases differ only slightly, the slope of the curves with equal optimal rotation length being more vertical with storms; and henceforth I present the results only for forest fires. Roughly speaking, an increase of one percentage point in the damage probability corresponds to a decrease of 10 or 15 $\text{€}/t_{CO_2}$ in the carbon price, respectively for storm and fire risks.

Under high carbon prices, the optimal rotation length is quite sensitive to how carbon is stored after a harvest or damage, embodied in the parameters β and γ . The parameter γ affects the situation more – rather obviously – if the damage probability is high. Should more of the carbon be sequestered into long-term storage, thus implying a higher β , optimal rotation lengths would be shortened considerably. In particular, the infinite rotations would not take place, for it would become preferable to place the harvested carbon from successive rotations in permanent storage, rather than to store it in the

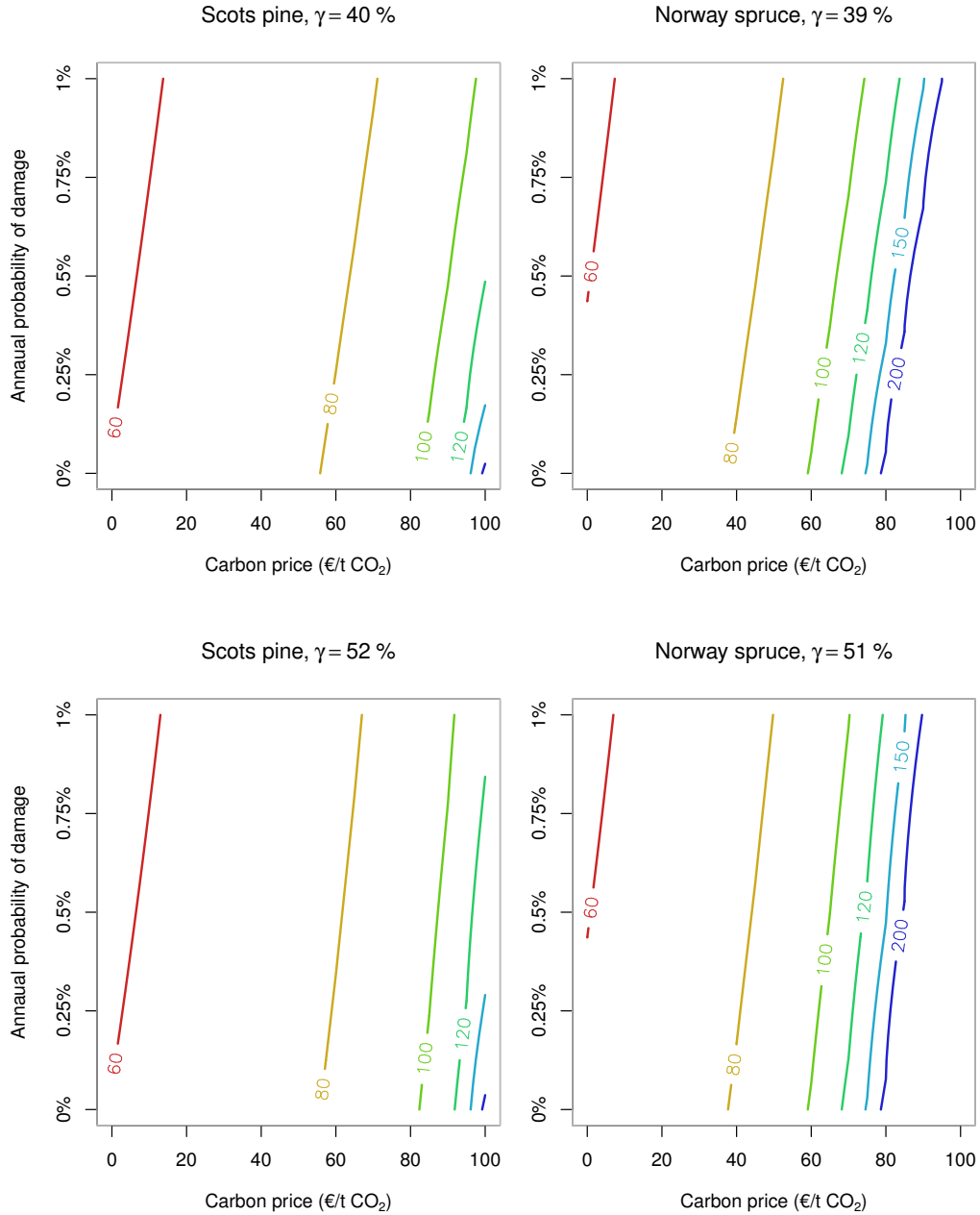


Figure 3: Optimal rotation length in years for different values of carbon pricing (x-axis) and annual probability of forest damage (y-axis). The top row considers forest fires and the bottom row storm damages.

growing forest stock.

3.3. Expected value and risk

Carbon pricing and damage risks have also a notable impact on the economic returns and risk for the forest owner. Figure 4 presents the LEV using equation (4) and the relative standard deviation of returns using Monte Carlo sampling.

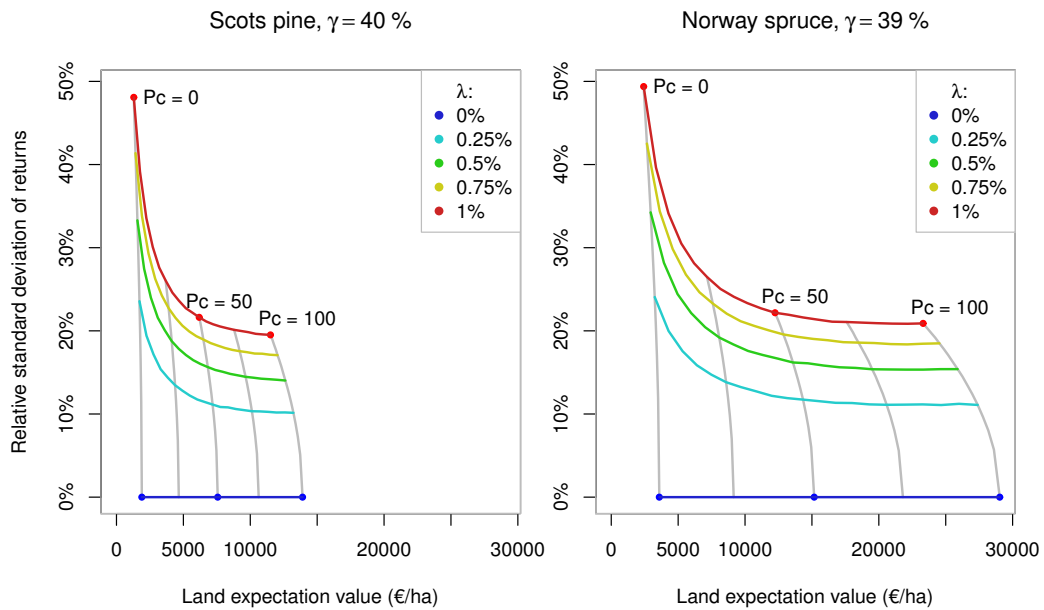


Figure 4: Land expectation value and relative standard deviation of returns for the optimal rotation under different carbon prices (in €/t_{CO₂}) and annual damage probabilities λ (indicated with colour). The grey lines denote 25 €/t_{CO₂} increments in the carbon price.

The land expectation value is multiplied from 7 to 9 fold across the range of carbon prices used here. Again, this effect is far more pronounced with spruce, which has a higher potential for sequestering carbon. Given this large discrepancy in LEV between the species, and although the two species prefer somewhat differing habitats, carbon pricing could affect species choice while re-planting the forest. The damage risk reduces the LEV somewhat.

The financial risk is obviously greater with a higher probability for damages. Carbon pricing, however, mitigates this risk effectively. For the highest damage probability considered here, the relative risk in returns is halved

across the range of carbon prices. If revenues are solely from harvests, a damage event postpones harvests and reduces the returns considerably.

On the other hand, under carbon pricing the forest owner receives revenues early-on from the increasing forest carbon stock, prior to a possible damage event. As the carbon stock is not released immediately to the atmosphere after forest damage, the forest owner is required to pay only a fraction of the forest carbon stock's value in net present value terms. Consequently, the damage risk affects the returns from carbon payments less than from timber sales. As the bulk of net returns comes from carbon payments under a high carbon price, the relative risk in returns is low.

3.4. Long-term average carbon stocks

The relative pricing between timber and carbon affects to which use landowners put their forests: towards producing raw material or to storing carbon. To illustrate this more concretely, I calculate the carbon stock and annualized harvests, averaged over a long time horizon in the manner of Pingoud et al (2018), for the optimal rotations under different carbon prices and damage probabilities. This can be interpreted as the long-term production possibility frontier between supplying timber and storing carbon, when the rotation length is determined in an economically optimal way³.

The average harvest yield with exponentially distributed damages equals the average yield from a single rotation divided with the average length of a single rotation:

$$\frac{e^{-\lambda T^*} v(T^*)}{\lambda^{-1}(1 - e^{-\lambda T^*}(1 + \lambda T^*)) + e^{-\lambda T^*} T^*}. \quad (7)$$

The calculation of carbon stocks is based on a Monte Carlo sampling of forest damages, and covers the living tree biomass, dead biomass due to forest damages, and wood products and harvest residues due to final fellings. The carbon stock of dead biomass and wood products are assumed to decrease with dynamics described in section 3.1.

The results from these calculations are presented in Figure 5 for the optimal rotation lengths of Figure 3. The longer rotations associated with higher carbon prices imply significantly higher carbon stocks and lower harvests, particularly with prices over 75 €/t_{CO₂}. With spruce, the carbon stocks are

³Note that the optimal rotation length does not maximize the long-term output due to discounting.

increased two to three times larger across the range of considered carbon prices, even with the highest probability of forest damages.

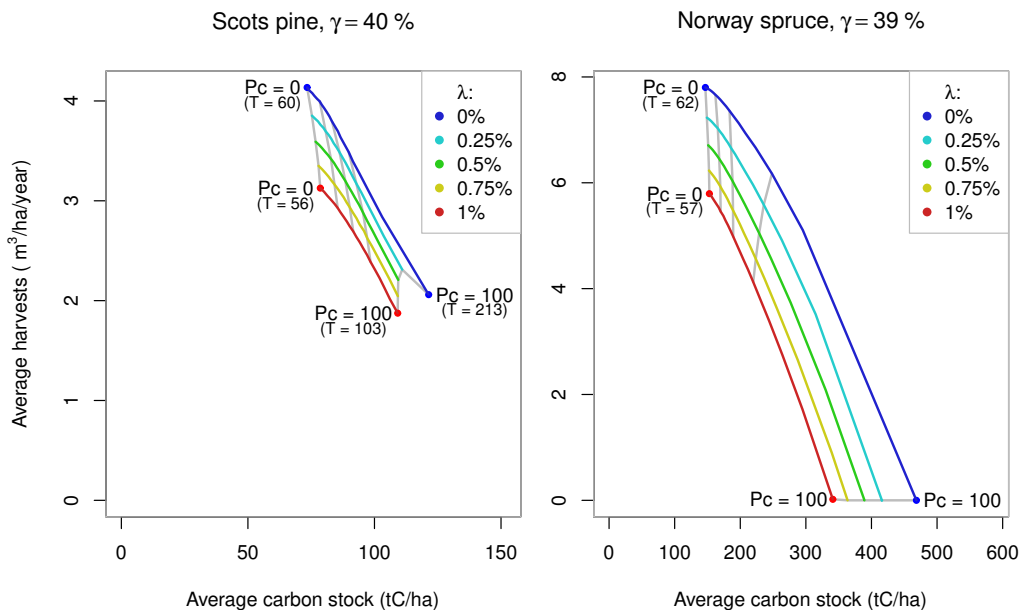


Figure 5: The long-term average of carbon storage (x-axes) and harvests (y-axis) under different carbon prices (in $\text{€}/t_{CO_2}$) and annual damage probabilities λ (indicated with colour). The grey lines denote 25 $\text{€}/t_{CO_2}$ increments in the carbon price.

As carbon price increases, there is first a gradual rise in rotation length, followed by a cut-off price after which the optimal rotation length becomes infinite, as was shown in Figure 3. Concomitantly, harvests can decline rapidly to zero with relatively small changes in the carbon price in Figure 5. From the perspective of raw-material production, harvesting decisions seem very sensitive for changes in carbon pricing with higher price levels. One could expect, however, that wood markets would react to such changes by parallel changes in timber prices.

4. Discussion

A policy that imposes a price for the flows of forest carbon would incentivize significant climate action in forest management, even in the presence of forest damage risks (Stainback and Alavalapati, 2004; Daigneault et al,

2010; Couture and Reynaud, 2011). Departing from the earlier studies, I also considered here the fact that the whole carbon stock is not lost immediately after forest damage, even in the case of a forest fire. This lessens the damage risk's impact on shortening the rotation under carbon pricing, particularly if carbon prices are high.

An efficient policy would require the landowner to effectively pay for the carbon released due to harvests or forest damages. The numerical results reflected this principle, similarly to Stainback and Alavalapati (2004) and departing from Daigneault et al (2010) and Couture and Reynaud (2011); although the theoretical model allows also alternative specifications. Regarding forest damages, such policy would provide incentives for reducing the damage risk. For harvests, this would incentivize the uses of wood which store the carbon long-term. The practical implementation of who actually pays for the carbon release was left open here, but it was rather assumed that any subsequent release of forest carbon would be factored in the price of timber. Hence, the price P_f was assumed to exclude the value of embodied carbon, and the carbon payment due to harvest or damage was included explicitly in the calculation of LEV.

The pricing of forest carbon also increases considerably the revenues from forestry, leading to an increase in the price of land suitable for forest growth. This impact is a clear reflection of the gravity of the climatic problem. The incentive for afforestation would effect some of the mitigation potential (Sohn-gen and Mendelsohn, 2003), but also increase competition for land and lead to spillovers to other land-using sectors, such as agriculture.

The result also showed that carbon pricing decreases the relative risk in returns for the landowner, as carbon payments from forest growth generate early-on income during the rotation. With sufficiently high prices for carbon, the optimal rotation can extend to infinity, whereby all revenues for the landowner would arise from draining and storing atmospheric carbon. As a result, timber supply can become highly sensitive on carbon pricing, unless timber prices follow the changes in carbon price.

The analysis presented here did not touch on the discount rate. In financial models, one commonly assumes that riskier investments require higher expected returns, which can be factored in to the net present value calculation through a higher discount rate. The results presented here showed that carbon pricing would reduce the economic risk from forest damages. While this would imply a lower discount rate in itself, one should also consider future volatilities in timber and carbon prices (Chladná, 2007; Guthrie

and Kumareswaran, 2009) in order to form a comprehensive picture on the associated risks.

It is yet difficult to imagine how one could construct meaningful price forecasts multiple decades into the future. Timber prices fluctuate according to supply and demand, which are hard to predict in the long term. Carbon prices are prescribed by climate policy; but in an idealized sense depend ultimately on our understanding of the climate problem's severity, possibly being very volatile (Ekholm, 2018). Optimal strategies for climate change mitigation involve increasing carbon prices, which also affects forest management by lengthening the rotation (Ekholm, 2016). Future research should look into how strongly timber prices could keep up with a rising carbon price, perhaps driven by an increasing demand for renewable raw materials.

The optimal balance between the supply of carbon storage and renewable raw-material is not, therefore, clear-cut. The answer lies on the relative pricing between carbon and timber. While the presented results implied a major increase in forest carbon stocks due to a moderate price on carbon – in itself implying strong contribution to climate action – the employed static setting did not account for possible price reactions from the timber market. Such responses would return the balance back towards timber production, but the question remains on how much. Similarly, the extent to which carbon pricing could induce afforestation rests on how fiercely other sectors respond to the increased competition for land. To explore these aspects, future research should apply dynamic, integrated analyses to go beyond the static-price, single-sector setting used here (Sohnngen and Mendelsohn, 2003). Nevertheless, without a carbon-pricing policy for forests, a major opportunity for mitigating climate change might not be realized.

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