Forest Policy and Economics 62 (2016) 62–68

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Optimal forest rotation age under efficient climate change mitigation

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ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 7 September 2015
Accepted 20 October 2015
Available online 4 November 2015

Keywords:
Optimal forest rotation
Carbon pricing
Climate change mitigation

ABSTRACT

This paper considers the optimal rotation of forests when the carbon flows from forest growth and harvest are priced with an increasing price. Such evolution of carbon price is generally associated with economically efficient climate change mitigation, and would provide incentives for the land-owner for enhanced carbon sequestration. For an infinitely long sequence of even-aged forest rotations, the optimal harvest age changes with subsequent rotations due to the changing carbon price. The first-order optimality conditions therefore also involve an infinite chain of lengths for consecutive forest rotations, and allow the approximation of the infinite-time problem with a truncated series of forest rotations.

Illustrative numerical calculations show that when starting from bare land, the initial carbon price and its growth rate both primarily increase the length of the first rotation. With some combinations of the carbon pricing parameters, the optimal harvest age can be several hundred years if the forest carbon is released to the atmosphere upon harvest. In the near term, however, a higher growth rate of carbon price can lead to shorter rotations for forests that are already near their optimal rotation age, indicating that the effect of carbon price dynamics on optimal rotation is not entirely monotonous. The introduction of carbon pricing can also have a significant impact on bare land value, and in some considered parametrizations the land value was based solely on its potential to capture and store atmospheric carbon.

1. Introduction

Forests are in a natural interaction with atmospheric carbon dioxide, the main driver behind anthropogenic climate change. A growing tree stores carbon from the air in itself, which is later released back to the air through fires, natural decay of the biomass, or human-induced activities. Forests involve globally both large stocks and flows of carbon, making them an important element in the context of climate change and its mitigation.

Achieving stringent targets of climate change mitigation – e.g. the 2 °C limit considered currently in the United Nations' climate negotiations – have been estimated to require significant economic effort. Therefore it is of importance that mitigation is implemented in an economically efficient manner, putting the mitigation resources in the best possible use. A general view in economics states that this could be achieved by pricing all carbon dioxide flows to and from the atmosphere with a uniform price across the economy.

Such pricing can be implemented in forestry by crediting a forest owner for the carbon absorbed due to forest growth, and taxing for the carbon that is released back to the atmosphere. The latter would occur e.g. if the tree biomass is harvested and combusted for energy, through the gradual decay of forest products and litter, or due to forest fires. On the other hand, if the harvested wood's carbon is stored permanently, the atmospheric release and the subsequent levy for the forest owner could be avoided – perhaps at least partially – creating an incentive for the long-term storage of the harvested wood's carbon.

Pricing of forest carbon flows and its implications for forest management have been studied previously in forest economics. The optimal rotation age of even-aged stands under constant carbon pricing has been examined e.g. by Plantinga and Birdsey (1994), van Kooten et al. (1995) and Hoen and Solberg (1997). Later contributions have also considered additional forest management options, such as fertilization (Stainback and Alavalapati, 2002) and thinnings (Pohjola and Valsta, 2007). Analyses of forestry carbon pricing as a part of the larger macroeconomy have also been presented (Tahvonen, 1995; Sohngen and Mendelsohn, 2003). A main conclusion from these studies has been that the pricing of forest carbon lengthens the rotations on the stand-level, leading to a larger forest carbon stock and thus a higher amount of sequestered atmospheric carbon.

The stand-level analyses referenced above have assumed a constant price for carbon. However, an economically efficient climate policy generally implies an increasing carbon price. This is a common result from numerous numerical scenarios addressing efficient climate change mitigation (see e.g. Nordhaus, 2010). An analytical solution for limiting the temperature increase below 2 °C in a cost-efficient manner suggested that the carbon price increase should be close to exponential for several decades (Ekholm, 2014). Although an increasing carbon price has been a part of e.g. macroeconomic approaches using intertemporal optimization (Sohngen and Mendelsohn, 2003) and an analysis on the decision

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http://dx.doi.org/10.1016/j.forpol.2015.10.007

to convert land to carbon storage through afforestation (van't Veld and Plantinga, 2005), this feature has been absent from stand-level analyses of optimal forest rotation length.

The purpose of this paper is to analyze the forest-owner's problem of maximizing the net present value of forest revenues from even-aged rotations in a case where the changes in tree carbon stock are priced with an exponentially increasing price. The paper provides a generalization to the constant-price approach of van Kooten et al. (1995), employing the same problem formulation and numerical parameters to allow a direct comparison with their results. With the consideration of exponentially increasing prices – contrasting from the case of constant prices – the problem setting described here is not stationary, but changes over time as the carbon price grows. This implies that the optimal harvest ages differ on subsequent rotations, and the optimal rotation length for the same type of forest changes over time.

The paper is structured so that the problem setting is described in Section 2, followed by a derivation for the first-order optimality conditions. Section 3 provides numerical examples of optimal rotation ages when starting from bare land, the implications of increasing carbon pricing to bare land value, and the currently optimal harvest ages; using the forest growth curves and parameters from van Kooten et al. (1995). The role of these calculations is to illustrate the problem setting – how carbon pricing under economically efficient climate change mitigation might affect forest economics – and further research should analyze optimal strategies for various actual forest stands. Finally, Section 4 discusses the results' implications on a broader context.

2. An analytical consideration

The considered forest-owner's optimization problem is to maximize the present value of net revenues from even-aged rotations of a forest plot that is initially bare land, when timber price remains constant and all carbon flows to and from the atmosphere are priced with an exponentially increasing price. Each harvest yields a volume of wood that can be sold at a constant price, but also necessitates a costly replanting of the subsequent forest stock. The forest-owner is credited for each tonne of carbon sequestered by the forest during its growth, and is taxed for each tonne of carbon released back to the atmosphere, both with a carbon price that increases exponentially. The release is assumed either to take place immediately after harvest, disregarding temporary stocks of forest products or carbon in the soil; though allowing that a certain fraction of the harvested carbon will be stored indefinitely and thus not being levied for the atmospheric carbon release. Knowing the assumed growth of the carbon price with perfect foresight, the forest-owner chooses an infinite sequence of rotation lengths T_1, T_2, T_3... that maximize the value of the bare land.

The maximization problem, defined at time t, can be formulated as:

$$\max_{T_1,T_2,\ldots}\sum_{i=1}^{\infty}\left[\int_0^{T_i}\alpha P_c e^{(\rho-r)\left(t+\tau+\sum_{j=1}^{i-1}T_j\right)}v'(\tau)\mathrm{d}\tau + e^{-r\left(t+\sum_{j=1}^{i}T_i\right)}\left[\left(P_f-\alpha(1-\beta)e^{\rho\left(t+\sum_{j=1}^{i}T_j\right)}P_c\right)v(T_i)-C\right]\right], \tag{1}$$

where,

- T_i is the length of the ith rotation,
- P_c is the carbon price at time $t=0$ ($/tC),
- P_f is the price of timber ($/m^3),
- r is the real discount rate applied by the forest owner,
- ρ is the annual real growth rate of the carbon price,
- $v(\tau)$ is the stem volume at age τ (m^3/ha),
- α is a conversion factor between stem volume and total carbon mass (tC/m^3),
- β is the share of carbon stored permanently after fellings,
- C is the forest regeneration cost ($/ha).

The first term in Eq. (1) represents the carbon credits accrued from forest growth during the rotation. The increase in forest carbon stock is given by $\alpha v'(\tau)$, valued with a carbon price which increases with the rate ρ. The second term sums over timber revenues with price P_f, carbon cost and regeneration costs C at the end of rotation when the forest volume is $v(T_i)$. Both terms are summed over different rotations i, and discounted with rate r to time $t=0$. In order to ensure the present value remains finite, it is required that $r>\rho$, i.e. that the discounting applied by the forest owner is stronger than the growth rate of the carbon price.

The optimal value of the objective function in problem (1) – defined at time t – can be denoted with a value function $V(t)$. Should the forest's value be based solely on the net present value of revenues and costs from timber, carbon and regeneration; $V(t)$ represents the bare land value at time t, discounted to time zero. Using the value function, the problem can be written in a recursive form, where the value of rotations beyond the first is given by $V(t+T_1)$, i.e. the optimal value of the problem (1) defined at time $t+T_1$. The recursive formulation is

$$\max_{T_1}\quad \underbrace{e^{-rt}\left(\alpha P_c e^{\rho t}\int_0^{T_1}e^{(\rho-r)\tau}\nu'(\tau)d\tau + e^{-rT_1}\left(\left(P_f-\alpha(1-\beta)e^{\rho(t+T_1)}P_c\right)\nu(T_1)-C\right)\right)+V(t+T_1)}_{:=f(t,T_1)}, \tag{2}$$

where the value function $V(t+T_1)$ returns the optimal value from subsequent rotations, but which depends on the first rotation's length T_1. In this recursive formulation, let us denote the objective function of Eq. (2) with $f(t,T_1)$.

The first-order condition of Eq. (2) for an optimal rotation age T_1^* is

$$\begin{aligned}&e^{-r(t+T_1^*)}\left(\left(\alpha\beta P_c e^{\rho(t+T_1^*)}+P_f\right)\nu'(T_1^*)\right.\\&\left.+\left(\alpha(1-\beta)(r-\rho)P_c e^{\rho(t+T_1^*)}-rP_f\right)\nu(T_1^*)+rC\right)\\&+V'(t+T_1^*)=0\ .\end{aligned} \tag{3}$$

This equation does not yet allow the solving of the optimal rotation time T_1^*, because it involves $V'(t+T_1^*)$, the derivative of the unknown value function at time $t+T_1^*$. However, an expression for $V'(t)$ can be formulated by using the envelope theorem to the objective function $f(t,T_1)$ at T_1^*:

$$\begin{aligned}\frac{dV(t)}{dt}&=\left.\frac{\partial f(t,T_1^*)}{\partial t}\right|_{T_1^*=\operatorname{argmax}_{T_1} f(t,T1)}\\&=\alpha P_c(\rho-r)e^{(\rho-r)t}\left(\int_0^{T_1^*}e^{(\rho-r)\tau}\nu'(\tau)d\tau\right)\\&\quad-\left(\alpha P_c(1-\beta)(\rho-r)e^{(\rho-r)(t+T_1^*)}+rP_f e^{-r(t+T_1^*)}\right)\nu(T_1^*)\\&\quad+e^{-r(t+T_1^*)}rC+V'(t+T_1^*)\ .\end{aligned} \tag{4}$$

The expression for $V'(t)$ in Eq. (4) involves the optimal rotation age T_1^*, which therefore has to satisfy also the first-order conditions for the optimization problem defined at time t. Hence, one can solve $V'(t+T_1^*)$ from Eq. (3) and insert this into Eq. (4). This yields

$$\begin{aligned}V'(t)&=\alpha P_c(\rho-r)e^{(\rho-r)t}\left(\int_0^{T_1^*}e^{(\rho-r)\tau}\nu'(\tau)d\tau\right)\\&\quad-e^{-r(t+T_1^*)}\left(e^{\rho(t+T_1^*)}\alpha\beta P_c+P_f\right)\nu'(T_1^*)\ .\end{aligned} \tag{5}$$

A final form for the first-order condition is achieved by setting $t=0$, using Eq. (5) to write an expression for $V'(t+T_1^*)$, and by inserting this into Eq. (3). Now $V'(T_1^*)$ involves also the length of the second