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Optimal carbon storage in even- and uneven-aged forestry

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ABSTRACT

We study the effects of forest carbon storage on optimal stand management by applying a model where optimal harvests are partial cuttings, implying uneven-aged forestry, or both partial cuttings and clearcuts, implying even-aged forestry. Optimal carbon storage postpones partial cuttings and increases stand volume along the rotation. Carbon pricing may shorten or lengthen the rotation period depending on interest rate and speed of carbon release from wood products. If the carbon price is high, the shadow value of forest biomass is negative, implying that a higher interest rate leads to higher stand density. In empirically realistic examples, carbon pricing causes a switch from clearcuts to continuous cover management rather than vice versa.

1. Introduction

Forest ecosystems hold more than double the amount of carbon in the atmosphere (FAO, 2006). Carbon storage can be enhanced by reducing deforestation and increasing afforestation, but also by changing forest management in existing forests. The latter option may help prevent price increases of agricultural land and products. As the present stand-level literature mostly deals with changing the rotation period, a wider set of management adaptation options has remained unexplored. Our study applies a generalized stand-level model, where optimal harvests are solely partial cuttings, or both partial cuttings and clearcuts. This model allows the joint optimization of wood production and carbon storage in uneven-aged and even-aged forestry. We show that, in addition to the rotation period, economically efficient carbon storage also changes stand density along the rotation and, in many cases, the optimal management regime from even-aged to uneven-aged management.

An extensive body of literature exists on carbon storage and afforestation potential on a national level (e.g. Lubowski et al., 2006; Mason and Plantinga, 2013). At the stand level, a seminal paper by van Kooten et al. (1995) examines the effect of carbon taxes and subsidies on optimal rotation age. Their numerical results suggest that internalizing carbon benefits tends to increase rotation ages only moderately. The numerical study by Stainback and Alavalapati (2002) on slash pine forests in the southern U.S. suggests that carbon storage increases sawtimber yields but decreases pulpwood yields, and considerably increases the value of forestland. Guthrie and Kumareswaran (2009) study the effect of carbon credit schemes on the length of rotation period under stochastic timber prices. Olschewski and Benítez (2010) show that carbon storage increases optimal rotation length considerably in tropical fast-growing stands. Akao (2011) shows using an extended Faustmann model that carbon storage may shorten or lengthen the optimal rotation. Hoel et al. (2014) develop the approach in van Kooten et al. (1995) by including forests' multiple carbon pools and the use of wood for bioenergy.

These studies (as well as many others) apply the generic Faustmann rotation model (Samuelson, 1976), where forests can be harvested by clearcutting only. As such, this model is best suited for forest plantations, which, however, account for only 7% of global forest area (Payn et al., 2015). How well this model is suited for more natural forests is questionable. Moreover, risks induced by climate change may favor more diverse management practices in semi-natural forests and even in areas currently dominated by the rotation regime (Gauthier et al., 2015). The main alternative is uneven-aged or continuous cover forestry, which applies partial cuttings (i.e. thinnings) and relies on continuous natural regeneration. Compared to even-aged forestry, this regime is likely to be more favorable to many forest-dwelling species (Calladine et al., 2015) and more resilient against the many threats of climate change (Thompson et al., 2009). Thus, clear interest exists in exploring whether carbon storage favors uneven-aged forestry compared to even-aged forestry or vice versa.

Goetz et al. (2010) study uneven-aged forestry and carbon storage, but do not analyze the choice between management regimes. Pukkala et al. (2011) study the regime choice, but apply a model without sound economic basis. Gutrich and Howarth (2007) raise the question of management regimes with carbon storage, but the choice is analyzed without optimization. Thus, the question of whether carbon storage favors continuous cover or clearcut forestry is completely open. Our

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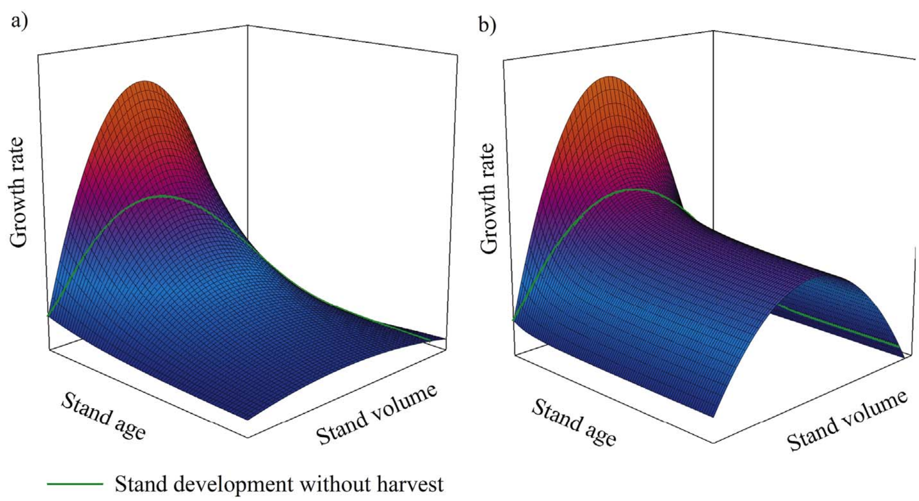

Fig. 1. Stand development a) without natural regeneration and b) with natural regeneration.

objective is to answer this question analytically using a model with sound economic basis and that covers both management alternatives simultaneously.

The economics of uneven-aged management has been studied since Adams and Ek (1974). While most models attempt to circumvent the dynamic complexities of optimizing uneven-aged management,[1] Haight (1985) and Haight and Getz (1987) specify and numerically compute a theoretically sound dynamic optimization model for uneven-aged management. In another line of research, Chang (1981) and Chang and Gadow (2010) study optimal partial cutting cycles and growing stocks in uneven-aged stands, while Parajuli and Chang (2012) extend the model with carbon sequestration. Recently it has been shown that both clearcut and continuous cover management can be covered by a single framework (Tahvonen, 2015, 2016). In Tahvonen (2016), the Clark (1976, p. 263–269)[2] assumptions on forest aging are revised to account for natural regeneration. This leads to an analytically solvable model that includes both forest management regimes and their optimal choice. In the present paper, the model is further extended to include carbon storage.

Unlike all previous studies, our study analyzes optimal carbon storage without restrictions on the management system. This allows us to show that the set of economically efficient methods for enhancing carbon storage in forests is much wider than previously thought. We show analytically that carbon pricing may either increase or decrease the optimal rotation age, depending on assumptions on interest rate and carbon release from wood products. When carbon pricing increases rotation length, it tends to cause a switch from clearcuts to continuous cover forestry. This regime shift follows when the model is computed using empirically realistic parameter values. Additionally, we show that carbon storage postpones the beginning of thinning and increases stand volume before the possible clearcut. If the carbon price is very high relative to wood price, the shadow price of stand volume is negative, as the scarce resource is not wood but the remaining capacity for carbon sequestration. These effects have remained unnoticed in both studies based on the generic Faustmann model and studies that include thinning in numerically computed frameworks. All these results are new and reveal that carbon storage implies major changes in the established understanding of managing forest resources.

We continue by introducing the model and deriving the optimality conditions. This is followed by an analysis of optimal thinning, after which we present results on optimal rotation and management regime choice. Empirical and numerical examples are given alongside with analytical results. The proofs can be found in the appendix.

2. An economic model for wood production and carbon storage with endogenous management regimes

Let $x(t)$ denote the stand volume ($m^3\,ha^{-1}$) and $h(t)$ the rate of harvested volume ($m^3\,a^{-1}\,ha^{-1}$) in thinning. Regeneration cost is w, annual interest rate δ, and stumpage price p. At the initial moment t_0 the stand volume is x_0. Stand volume develops as a product of aging $g(t)$ and density-dependent growth $f(x)$:

$$\dot{x} = g(t)f(x(t)) - h(t), \quad x(t_0) = x_o. \tag{1}$$

Clark (1976, p. 264) assumes that f is single-peaked and that growth of old stands finally ceases independently of volume, i.e. $g'(t) < 0$ and $g(t)\to 0$ as $t\to\infty$. These assumptions on aging may be suitable if the model describes the growth of trees planted at t_0 and no natural regeneration occurs, i.e. a pure planted forest. Given this assumption, the outcome is a finite optimal rotation. However, if new saplings can emerge into the stand without planting, density-dependent growth may occur even in an "old" stand. To include natural regeneration, assume that $g(t)f(x)$ may remain strictly positive as $t\to\infty$. Suppose further that the aging function g and the growth function f are continuous and twice differentiable and

$$f(0) \geq 0, \ f(\underline{x}) = 0, \ f''(x) < 0, \ f'(\hat{x}) = 0, \ 0 < \hat{x} < \underline{x}, \tag{A1}$$

$$g(0) > 0, \ g'(t) < 0, \ g''(t) > 0, \ \lim_{t\to\infty} g(t) = \tilde{g} > 0, \tag{A2}$$

$$\tilde{g}f'(0) > \delta, \tag{A3}$$

where $\underline{x}$ is the carrying capacity of the site, and $\hat{x}$ denotes the growth-maximizing stand volume. Assumption (A3) restricts the analysis to outcomes where continuous cover solutions are not *a priori* ruled out. Fig. 1a shows the original Clark (1976) growth function and Fig. 1b a modified function that satisfies Assumptions (A1) and (A2).

Let $p_c \geq 0$ denote the economic value of one CO_2 unit, $\mu > 0$ the amount of CO_2 per one unit of wood, and $p_c\mu\alpha$ the value of released CO_2 per one unit of harvested wood. If wood is burned immediately we set $\alpha = 1$, as implicitly assumed in the current New Zealand carbon credit system (Manley and Maclaren, 2010; Adams and Turner, 2012). If carbon storage in wood products is permanent, it may be possible to assume $\alpha = 0$. If CO_2 is instead gradually released as each wood product decomposes according to its specific qualities and usage, we set $0 < \alpha < 1$ (see Appendix A).

The optimization problem takes the form

[1] Various lines of research have been discussed in e.g. Getz and Haight (1989) and Rämö and Tahvonen (2014).

[2] Recall that Faustmann (1849) included thinning in his bare land formula, but remained silent about the possibilities of harvesting trees by thinnings only. A similar route is followed by Clark (1976), while Samuelson (1976) neglects thinning altogether. Halbritter and Deegen (2015) extend the continuous-time thinning and rotation model with a focus on optimized artificial regeneration.