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A critical view on benefit-cost analyses of silvicultural management options with declining discount rates

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ABSTRACT

The long planning perspective is one of the unique features of forestry. How to value money flows expected in the far distant future is therefore a crucial question. Applying time declining discount rates (DDR) may offer an appropriate alternative to conventional discounting, but few studies have applied DDRs in forest economics. We expect that theoretical assumptions behind welfare analyses based on DDR will be important. Using a dataset from the UK (Davies and Kerr (2015) [Forests 6: 2424–2449]) we investigate the effects of 1) more than marginal contributions from forestry to consumption, 2) the role of the assumed scenarios for return on capital, and 3) ignoring optimization (i.e. adopting predefined management scenarios) on the ranking of different silvicultural strategies. These include various clearfelling options (with replanting, natural regeneration or underplanting) and the transition to continuous cover forestry. Our analysis reveals that changes in these aspects affect the ranking of forest management options more strongly than a pure change in the coefficients of a benefit cost analysis. Decreasing marginality, cautious assumptions about the worst-case return on capital and optimization of silvicultural operations all increase the relative attractiveness of continuous cover forestry. We conclude that applying DDR makes valuation in forestry more demanding and should be applied with appropriate care. In addition, the precise assumptions behind the particular schedule of DDRs should be explicit. Finally, theoretical considerations support the importance of combining optimization of silvicultural management strategies with their economic evaluation.

1. Introduction

Planted forests contributed 46% of the world's industrial roundwood in 2012 (Payn et al., 2015). Plantations are usually monocultures, managed in short rotations, whereby a cycle concludes with clearfelling all timber (Cubbage et al., 2007). Alternative silvicultural management methods, such as closer-to-nature approaches using mixed tree species and maintaining a continuous cover of older trees, are less often applied (Puettmann et al., 2015). Economic considerations are a major factor limiting the uptake of alternative silvicultural methods, because the transition phase to continuous cover forestry may lead to losses compared to the clearfell system. The economic attractiveness of management options hinges heavily on the evaluation of such intertemporal choices. Discounting is the usual method to support intertemporal decision-making in international forest economics and forest management optimization (Amacher et al., 2009).

However, using discounting to evaluate the future benefits and costs of forest management often leads to recommendations that are different from the forest management schemes developed in practice (Möhring, 2001). Usual recommendations resulting from discounting include shortening rotations, reducing forest densities, and introducing monocultures comprised of fast growing, often exotic tree species. These recommendations, however, strongly depend on the discount rate. For example, Brukas et al. (2001) showed for Baltic forestry that setting a discount rate of $r = 0.03$ would lead to much shorter rotation periods and significant shifts in tree species composition. Concerned about these results, they suggested discount rates of around $r = 0$–0.02 for public forestry. Moreover, aiming for the highest (theoretical) level of economic efficiency often results in discontinuous management and timber flows (Tahvonen and Kallio, 2006; Hahn et al., 2014). Discounting with higher discount rates therefore often challenges the sustainable yield paradigm. These consequences of using a mathematical economic calculus to inform forest management led very early to controversial and often quite emotional discussions among foresters (Fernow, 1911). In these discussions, some forest scientists have suggested "maximum sustained yield" as the only valid criterion to optimize forest management, based on a discount rate tending to zero. In contrast, other authors have advocated the maximization of the land

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rent through discounting with a rate greater than zero. For example, Samuelson (1976) questioned the argument that for a forest property in a steady state (i.e. a fully-regulated forest), no interest rate needs to be considered in management decisions. The world's plantation forestry still follows the maximization of the net present value using constant, at times quite high, discount rates (Cubbage et al., 2007). Consequently, the apparent long-lasting conflict between sustainable forest ecosystem management and the conventional economic approach to maximize the present value of future benefits and costs, continues (e.g. Toman and Ashton, 1996). In this context Hepburn and Koundouri (2007) confirm a considerable interest in the conceptual basis for discounting and the selection of the discount rate in forest economics, but not many studies have been carried out since then (with a few exceptions, such as the study by Price, 2011).

Consensus is now growing in the economics literature about time-declining discount rates (DDRs) as an option for a more appropriate evaluation of the far distant future (e.g. Freeman et al., 2015). This approach places higher value to benefits and costs in the far distant future than conventional discounting and is possibly a means to more appropriately acknowledge the benefits and costs of alternative silvicultural systems that are associated with long-lasting consequences.

Forestry provides an ideal example for applying DDRs, because the consequences of forest decision-making reach very far into the future. However, forest economics studies associated with DDRs are still rare. One example is Hepburn and Koundouri (2007), who discuss using DDRs to evaluate forest projects in general. Another example is Price (2011), who investigated the optimal rotation with DDRs.

Davies and Kerr (2015) applied DDRs to calculate net present values for clearfelling based and continuous cover forestry in Sitka spruce (*Picea sitchensis* (Bong.) Carrière). Their schedule for DDRs follows a suggestion in the HM Green Book (2003), which is a UK guide for the appraisal and evaluation of Central Government projects. The main aim of this guide is to ensure "… that public funds are spent on activities that provide the greatest benefits to society, and that they are spent in the most efficient way …" (HM Green Book, 2003, p. V).

The study by Davies and Kerr (2015) is valuable because Great Britain is a good example for Central European plantation forestry with fast growing, exotic tree species. Concerns about this type of forest management and discussions about alternative silvicultural methods already started some decades ago (Cameron et al., 2001) and are ongoing. Davies and Kerr (2015) compare DDRs with conventional discounting, but their results do not reveal any substantial differences in the ranking of alternative silvicultural management options when applying DDRs. Two clearfelling options, one with and one without natural regeneration, clearly outperform the alternatives, although the continuous cover option shows favorable economic results after an 83 years period. Continuous cover forestry consistently obtained the worst ranking, which is likely to be an effect of discounting, even though the ranking remained quite robust when applying alternative discount rates (Davies and Kerr, 2015). Given the applied evaluation guide (HM Green Book, 2003) focusing on government projects across all sectors of the economy, it is important to review the assumptions that may strongly influence the results of the evaluation, for example when carried out in other contexts. A general problem of carrying out benefit-cost analyses (BCA) about silvicultural management scenarios is also the definition of such scenarios. It is of great interest how the evaluation of pre-defined treatments may influence the results of the BCA of silvicultural options.

The objective of our paper is to increase the awareness of the theoretical foundation of declining discount rates and of the distinction between non-marginal and marginal values in the forest economics' community. This is achieved by analyzing the impact of important implicit assumptions behind the analyses by Davies and Kerr (2015). The tested assumptions will explicitly relate to (A) the marginality of the evaluated projects, (B) the schedule of the discount rates applied, and (C) the definition of the silvicultural management concepts.

In the following section (chapter 2) we will briefly review papers dealing with DDRs. Based on experiences from other scientific fields, we will then outline the key assumptions of DDR analysis carried out by Davies and Kerr (2015) in chapter 3. In chapter 4 we analyze important theoretical aspects of BCA for public projects, present a methodology, adopted from Gollier (2010), for consistently deriving various schedules for DDRs, and describe the silvicultural scenarios investigated. We also introduce theoretical considerations regarding optimizing the timing of silvicultural operations in chapter 4. In chapter 5 we present the results for four silvicultural alternatives and analyze the possible impact of the optimization of silvicultural operations, before concluding with some remarks about the importance of cautious consideration of assumptions behind BCA with DDRs.

2. Support of declining discount rates

DDRs mean that the rate of fall of the discount factor (i.e. the discount rate) declines over time, in contrast to conventional discounting, where the discount rate is constant. Many economic studies have raised concerns about the use of conventional discounting of future benefits and costs for valuing long-term investments. These concerns focus, among other issues, on intergenerational equity (e.g. Toman and Ashton, 1996). Consequently, applying DDRs has become particularly popular in the context of sustainability, climate change, nuclear waste and species extinction. The following section shall provide an overview on existing studies supporting DDRs that are relevant for questions regarding forest economics from various perspectives. We will thus include studies, discussing different approaches towards DDR that are not limited to the one method applied in the remainder of our study.

Following Price (2011), some studies in support of DDRs draw on observations of how people actually discount, while others give weight to the future from various perspectives, or derive conclusions from statistical analyses of real market returns. Some further studies also average assumed scenarios for either market return or consumption growth to analyze the impact on advisable discount rates. For example, Henderson and Bateman (1995) apply hyperbolic discounting to consider how people do actually discount the future. Newell and Pizer (2003) use US American market data to support DDRs. Li and Löfgren (2000) build on Chichilnisky (1997) and aggregate the perspectives of the present, represented by a utility stream discounted with a positive constant rate and of future generations, modeled as a utility stream discounted with a rate of zero. They show DDRs converging to zero in the very long run. Weitzman (1998) and Gollier et al. (2008) demonstrate how an appropriate averaging of scenarios (either for market return or for consumption growth) may lead to declining discount rates. Key messages include that it is not appropriate to average discount rates. Instead, discount factors need to be averaged, which would result in DDRs, at least if discount rates are positively correlated from year to year, i.e. being persistent. For an example of the critique on the usual practice of exponential discounting we may refer to Weitzman (1998, p. 202), who stated: "Few are the economists who have not sensed in their heart of hearts that something is amiss about treating a distant future event as just another term to be discounted away at the same constant exponential rate gotten from extrapolating past rates of return to capital."

One may separate the available approaches to DDR roughly into two groups: Support for DDRs may result from positive (descriptive) and from normative (prescriptive) approaches to analyzing intertemporal decision-making. People's behavior is often time inconsistent from a conventional discounting perspective, with individuals valuing time delays in the near future in a significantly different manner than time delays in the distant future. Following this observation, some authors draw striking analogies between human time preference and animal behavior (e.g. Henderson and Bateman, 1995; Hayden, 2016). Results of behavioral research are often more consistent with hyperbolic discounting, where the observed rate of fall of the discount factor is not constant but declines over time, which supports DDRs. While some recent studies reveal strong support for the use of hyperbolic discounting in actual decision-making (Wang et al., 2016), Rubinstein (2003) criticized hyperbolic discounting and proposed a procedural approach (based on similarity) to better describe and predict intertemporal choice. There is also empirical econometric work to analyze the development of the return on capital over long periods. These studies are relevant because the return on capital could serve as a discount rate. For example, Newell and Pizer (2003) included a random walk approach in their study and econometrically modeled DDRs because of the uncertainty of (positively correlated, and thus, persistent) US market interest rates. In conclusion, there appears to be ample evidence that discounting the near future more heavily compared to the far distant future suits human nature better than discounting with a constant rate. However, that people actually do discount based on declining rates does not necessarily mean that they should discount using DDR. Gowdy et al. (2013) argue that approaching the question of how social decisions about the future should be made by modeling how individuals value trade-offs between their own present and future well-being is problematic, because this question reflects issues of intergenerational equity rather than individual benefit. However, there is also strong support for DDRs from prescriptive research, which gives helpful insights about “optimal” decisions (i.e. how people should make their decisions). As mentioned above, prescriptive approaches either support DDRs by addressing the issue of economic sustainability directly, or they justify DDRs based on the uncertainty about future return on capital invested into the economy or on the uncertainty of future consumption change. Our study will analyze a prescriptive approach to DDRs.

In summary, many studies suggest alternatives to conventional exponential discounting to better support intertemporal choices addressing sustainability and/or the uncertainty in return on capital or changes in consumption. Independent from this line of thought, it is important to be aware that DDRs will percolate into practical applications. Countries such as Great Britain, France, Denmark and Norway have already integrated these ideas into their government guidelines for evaluating public projects (Freeman and Groom, 2014). In practice, however, applying a DDR to more appropriately consider future costs and benefits makes analyses more challenging (Arrow et al., 2012), and may therefore particularly complicate analyses in forest science (Price, 2011). It is consequently important that the assumptions behind DDRs and their possible consequences are clear.

3. Key-assumptions for applying DDRs in Davies and Kerr (2015)

Given that forest scientists and practitioners have long discussed the optimal silvicultural treatment of forests (e.g. Siiskonen, 2007; Puettmann et al., 2015), it is of great interest to analyze the key assumptions in Davies and Kerr (2015) in more detail. These assumptions relate to (A) the marginality of projects, (B) the schedule for DDRs and, (C) the omission of optimization, meaning to adopt pre-defined silvicultural management strategies.

(A) Marginality of projects

Regardless of whether discount rates are constant or declining, conventional BCA uses discounted cash flows aggregated to net present values for project assessment, which assumes that these projects are marginal. We will show that the standard welfare function, which consists of discounted utilities instead of discounted cash flows, will only be consistent with the evaluation of discounted cash flows when projects are actually marginal. Subsequently, we will test the impact of the marginality assumption on the ranking of the silvicultural options.

(B) Schedule for DDRs

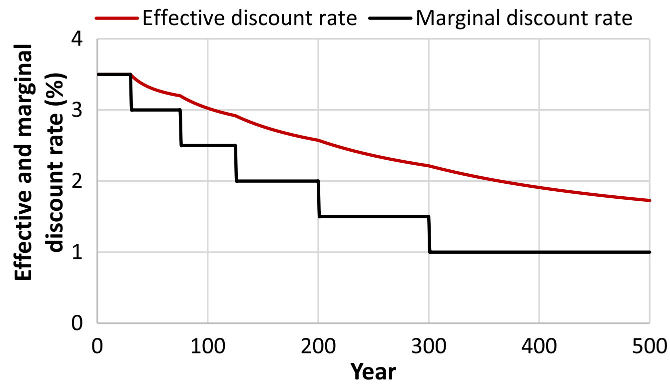

Fig. 1. Schedule of discount rates used by Davies and Kerr (2015).

As mentioned above, the HM Green Book (2003) forms the basis for the evaluations in Davies and Kerr (2015). It suggests a specific schedule of marginal discount rates, which decline over time (Fig. 1).

This guideline for the discount rate schedule generally refers to the “Ramsey” theoretical framework (Ramsey, 1928). Ramsey's consumption-based discount rate is a rate at which society should trade consumption in year t for consumption in the present (Arrow et al., 2012). It says that the social discount rate should consider the pure time preferences of people but also how consumption will change in the future, so that the current generation is not treated unfairly, when future generations would be able to consume more – and vice versa. Ramsey's model implies the identity of two terms, connecting time preferences and consumption growth (Eq. 1).

$$r_t - \rho = \gamma g_t <=> r_t = \rho + \gamma g_t \tag{1}$$

The left side of the equation is about time preferences and comprises the difference between the consumption (or social) discount rate, r_t, and the utility discount rate, ρ. The utility discount rate is the rate of impatience of people. The HM Green Book (2003) considers the rate of catastrophic risk and the rate of pure time preference to estimate ρ. The right hand side of the first term equation is the product of the consumption growth rate, g_t, and the index of constant relative risk aversion, γ, which authors also call inequality aversion (e.g., Arrow et al., 2012). γ “… is known as the elasticity of the marginal utility of consumption, the percentage change in the well-being derived from a percentage change in consumption (or income). The intuition behind … is that it expresses individuals' aversion to fluctuations in their income levels …” (Pearce et al., 2003, p. 130).

The Ramsey framework may act as an organizing principle to derive declining discount rates over long horizons and provides a useful framework for thinking about intergenerational discounting (Arrow et al., 2012). Under certain assumptions (e.g. marginality of the evaluated projects, see below) this approach is consistent with the objective to maximize discounted utility. A consumption-based discount rate following from the Ramsey model is recommended in the HM Green Book (2003) for discounting cash flows.

The Ramsey formula supports a prescriptive approach to decision making, i.e. suggesting how people should decide. However, as confirmed by Cropper et al. (2014), the HM Green Book (2003) adopts the specific decline of the discount rates based on empirical analyses in Newell and Pizer (2003). As mentioned before, Newell and Pizer (2003) derived declining discount rates from the uncertainty of (positively correlated) US market interest rates on capital over two centuries (1798–1999), based on long-term, high quality, government bonds (primarily US Treasury Bonds). Thus, the HM Green Book (2003) suggests a hybrid DDR schedule which combines the Ramsey theory with an empirical analysis (Cropper et al., 2014). Here we use an approach for deriving the schedule of discount rates consistent with that suggested by Gollier (2010), which assumes that consumption and, thus consumption growth, are uncertain. This approach acknowledges that people should and will adjust their consumption plans based on the expected return on capital invested in the economy. Subsequently, we will analyze how the assumed worst-case scenarios about the future return on capital and the degree of risk aversion both influence the results of the BCA carried out by Davies and Kerr (2015).

(C) Pre-defined management alternatives

For the discipline of forest economics, it is interesting to analyze the impact of defining management scenarios in advance of the economic evaluation, which do not implicitly consider any kind of formal economic optimization. This practice is not unusual in comparative forest economic studies (Tahvonen and Rämö, 2016). However, it will always remain uncertain if the investigated scenarios are really covering the potential that is inherent in a silvicultural management system.

4. Methods and data

4.1. Marginality of projects

4.1.1. Applying the discounted cash flow method

BCA is looking for projects promising the highest benefits to the society or the decision maker. In order to achieve this, BCA ranks projects based on their achieved net present value, resulting from summing of all appropriately discounted cash flows (considered as consumption equivalents) (Arrow et al., 2012). If the discounted consumption equivalents are marginal (i.e. they do not alter the marginal utility of the aggregate business-as-usual consumption), the alternative with the highest sum of discounted cash flows will also maximize the sum of the discounted utilities, with the latter being a standard in welfare analyses (Botzen and van den Bergh, 2014). The following proposition and proof are adopted from Dietz and Hepburn, 2013, with alterations.

Proposition 1. If $U(C_t + \Delta_t) = U(C_t) + U'(C_t)\,\Delta_t$, then

$$\sum_{t=0}^{\infty} \Delta_t \left(\frac{1}{1+r_t}\right)^t > 0 \langle = \rangle \sum_{t=0}^{\infty} [U(C_t + \Delta_t) - U(C_t)] \left(\frac{1}{1+\rho}\right)^t > 0 \tag{2}$$

Δ_t is a cash flow at time, t, r_t is the consumption based discount rate, which may depend on time, $U(\cdot)$ is the utility function, and C_t denotes an aggregate business-as-usual consumption at time t, which generates utility $U(C_t)$ at time t, and ρ is the utility discount rate (Dietz and Hepburn, 2013). Note that this proposition is limited to projects with a positive sum of discounted cash flows. Proof 1 in Appendix A provides mathematical support of our proposition.

4.1.2. Assumptions to test the impact of non-marginality

A core-assumption in most public welfare analyses is that a hypothetical representative agent would maximize discounted utility of consumption, C_t, which is usually assumed as predictable with certainty. Botzen and van den Bergh (2014) demonstrate this for the example of economic analyses of the consequences of climatic change (Eq. 3).

$$W = \sum_{t=0}^{\infty} U(C_t) \left(\frac{1}{1+\rho}\right)^t \tag{3}$$

In Eq. 3, W is welfare. However, this approach would only be appropriate for a full BCA considering non-marginal values, while economic valuation typically assumes that the changes in the stream of business-as-usual consumption, C_t, caused by the evaluated additional project-based consumption, Δ_t, are extremely small (Dietz and Hepburn, 2013). Under this assumption, discounted cash flow analysis and discounted utility provide identical rankings, as proposed above. It is now interesting to test the impact of the assumption of marginality, because in some situations project cash flows may be non-marginal (for example in large private forest enterprises, but see discussion section for a critical view on this example). We will assume various business-as-usual consumption flows, C_t, to test the influence of the marginality assumption, based on declining consumption discount rates, r_t (Table 1). The cash flows published by Davies and Kerr (2015) for various silvicultural projects represent the project-based consumption equivalents, Δ_t needed for Eq. 4.

Table 1
Schedule of consumption discount rates, r_t, and the associated utility discount rates, ρ, as well as assumed change in consumption, g_t, according to HM Green Book (2003, p. 99) with amendments.

Period of years	0–30	31–75	76–125	126–200	201–300	301 +
Consumption discount rate, r_t	0.035	0.030	0.025	0.020	0.015	0.010
Implied utility discount rate, ρ	0.015	0.015	0.015	0.015	0.015	0.015
Implied change in consumption, g_t	0.020	0.015	0.010	0.005	0.000	− 0.005
r_t, adjusted to a Ramsey discrete time model	0.0353	0.0302	0.0252	0.0201	0.0150	0.0099

The additional utility obtained by a specific silvicultural option is then:

$$U_P = \sum_{t=1}^{\infty} [U(C_t + \Delta_t) - U(C_t)] \left(\frac{1}{1+\rho}\right)^t \tag{4}$$

In Eq. 4 the utility of the business-as-usual consumption stream is measured with and without the project-related changes, Δ_t. This accounts for the (normative) need to compare consumption plans with and without the project-related alterations (Frederick et al., 2002).

The HM Green Book (2003) assumes a standard utility function, $U(\cdot)$, reflecting constant relative risk aversion (CRRA) of the degree, γ, i.e.:

$$U(C) = \frac{C^{1-\gamma}}{1-\gamma} \tag{5}$$

It considers $\gamma = 1$, implying $U(C) = \ln C$. In addition, the HM Green Book (2003) assumes $\rho = 0.015$ and $g_{t \le 30} = 0.020$, which implies $r_{t \le 30} = \rho + \gamma g_{t \le 30} = 0.035$. However, this calculus provides continuous time, although the discounted cash flow analysis suggested by the HM Green Book (2003) is in discrete time. We may adjust the consumption discount rate for the nearer future ($t \le 30$) to discrete time, considering the utility discount rate, ρ, the degree of constant relative risk aversion, $\gamma = 1$, and the growth of consumption, $g_{t \le 30}$, and would obtain:

$$r_t = [(1+\rho)(1+g_{t \le 30})^{\gamma}] - 1 \approx 0.0353$$

Based on the above equation, Table 1 also contains the other discount rates, which apply to the more distant future, when discrete time is provided. The development of the aggregate business-as-usual consumption, C_t, is modeled in Eq. 4 as follows (Eq. 6), which uses the implied g_t from Table 1:

$$C_t \;=\; C_0 (1 + g_t)^t \tag{6}$$

We assume an artificial C_0 of £2000, £10,000, and £100,000 as starting values for C_t as well as one variant without consumption growth, providing: $C_t = C_0 =$ £2,000, to obtain hypothetical business-as-usual flows of consumption over time, C_t. This helps to test whether or not the initial project rankings change depending on the assumptions made about the marginality of the projects. Compared to hypothetical business-as-usual consumption flows of £2000, the project-based net cash flows, which can range from around −£2000 to around +£12,000 (Davies and Kerr, 2015), are rather large in some years (i.e. non-marginal). Compared with £100,000, however, such cash flows are rather small (i.e. marginal).

4.2. Schedule for DDRs

4.2.1. Deriving declining discount rates

A pivotal question in BCA under DDRs is how to derive the schedule for the discount rates (Arrow et al., 2012). In the HM Green Book (2003) the DDR path is a step function (Fig. 1, Table 1), but the derivation of the step function is not explained in detail. In contrast, Gollier (2010) suggested a consistent and explicit approach to derive DDR and illustrated three theoretical equations for this purpose, based on consumption growth (Ramsey model), net present value or net future value considerations. He unified all three approaches by considering flexible consumption plans, making these plans dependent on the return on capital invested into the economy, r_{cap}. Here we refer to Gollier's consumption growth approach, which is related to the Ramsey model. However, for being consistent with the discrete time analyses suggested by the HM Green Book (2003) we need to express the Ramsey based formula suggested by Gollier (2010) in discrete time.

Proposition 2.

$$r_t = exp\left(-\frac{1}{t}[\,ln\,EU'(\widetilde{C_t}) - ln\,EU'(\widetilde{C_0})] + ln(1+\rho)\right) - 1 \tag{7}$$

is the time dependent consumption-based discount rate in discrete time, accounting for uncertainty in consumption growth, where E symbolizes expected values, which may be formed based on scenarios associated with probabilities. Eq. 7 expresses the same as the original Ramsey formula, only in discrete time. Proof 2 in Appendix B supports our proposition.

In the first part of Eq. 7 we have an expression for the uncertain changes in consumption, i.e. the consumption growth, and in the second part we find the utility discount rate as an expression of people's pure time preference (and catastrophic risk). Eq. 7 underlines that the decline of the consumption-based discount rate is caused by the uncertainty inherent in estimating the level of consumption, now and in the future.

4.2.2. Numerical assumptions to derive declining discount rates

We still need to define our scenarios for consumption plans depending on the assumed return on capital, r_{cap}. We obtain the expected marginal utilities of consumption needed for Eq. 7, given n scenarios for consumption, according to Eq. 8:

$$\begin{aligned} EU'(\widetilde{C}_t) &= \sum_{i=1}^{n} w_i U'(C_{t,i}) \\ EU'(\widetilde{C}_0) &= \sum_{i=1}^{n} w_i U'(C_{0,i}) \end{aligned} \tag{8}$$

In Eq. 8, w_i is the probability for scenarios i, with $\Sigma w_i = 1$. Following Gollier (2010) we assume flexible consumption plans, which depend on the return on capital, meaning that in each scenario for consumption, $C_{t,i}$ and $C_{0,i}$, is controlled by $r_{cap,i}$. For each scenario we provide and justify in Appendix C: $C_{t,i} = C_{0,i}\,(1 + g_{t,i})^t$, an optimal $g_{t,i} = \left(\frac{1 + r_{cap,i}}{1+\rho}\right)^{\frac{1}{\gamma}} - 1$, and $C_{0,i} = \left(\frac{1 + r_{cap,i}}{1 + g_{t,i}}\right) - 1$, all of which depend on $r_{cap,i}$, which is the return on capital invested in the economy of scenario i.

We use three scenarios for possible return on capital, $r_{cap,i}$, each associated with the same probability, $w_i = \frac{1}{3}$. As we assume the included worst-case scenario, $r_{cap,wc}$, to be influential, we test various versions of this scenario. The three versions are: scenario 1 with $r_{cap,wc} = 0$, 0.002, 0.004, 0.006, 0.008, and 0.01, scenario 2 with $r_{cap,expected} = 0.035$ as the expected value, and scenario 3 with $r_{cap,optimistic} = 0.07 - r_{cap,wc}$.

Consistent with the HM Green Book (2003), we furthermore use a utility discount rate, $\rho = 0.015$, and constant relative risk aversion (i.e. inequality aversion), $\gamma = 1$. We also test for $\gamma = 2$, as a greater inequality aversion assumed by Gollier (2010).

4.3. Scenarios to model forest management options

4.3.1. Silvicultural scenarios in Davies and Kerr (2015)

Davies and Kerr (2015) assessed four different management options for public forest stands with Sitka spruce in Great Britain. They distinguished several scenarios (named slightly differently in our study), all starting in a conventionally established and managed forest stand at age 25. Scenario S1, "Clearfell and replant," forms the baseline and reflects the actual management practice. Here, all trees are clearfelled at age 58 after several previous thinnings; to reduce biotic damage to the new plantation by beetles (*Hylobius abietis* L.), the forest is replanted after a delay of five years (cf Davies and Kerr, 2015 for details). Scenario S2, "Natural regeneration and harvest later," transforms the stand into a simple, even-aged structure, but relies on natural emergence of seedlings for regeneration. Natural regeneration is expected from year 55 onwards. For the considered example, relatively dense and regular regeneration may be assumed. Scenario S3, "Underplant and harvest later," is similar to S2, but S3 uses planting instead of natural regeneration, which increases costs. In scenarios S2 and S3 the rotation is extended to 65 years. Finally, scenario S4, "Continuous cover forestry," transforms the stand into a complex, uneven-aged forest structure, where at least three age cohorts of tree layers are always present at the stand level. The last trees of the initial stand are felled at age 107, while the first regeneration is expected at year 56, resulting in a 51-year transition period. "Thinnings from age 30 to 72 aim to maintain stand basal area at around 30 m^2/ha, while crown thinnings from 79 to 100 years are intended to represent target diameter harvesting …" Davies and Kerr (2015, p. 2430). Regeneration harvests, with the first carried out at age 65, use 20% of the stand volume to establish new age cohorts.

The different scenarios lead to quite different streams of cash flows (Fig. 2), here considered as forgone (negative) or additional (positive) consumption units.

The concentration of cash flows is highest under "Clearfell and replant," where clearfelling generates high net revenues in a 63-year cycle. In contrast, net revenues are spread more evenly over time under "Continuous cover forestry," but only after a long period of 83 years with low returns. After this period, however, "Continuous cover forestry" achieves relatively high net revenues in 21–28 year cycles. Because of the long period with low cash flows, the NPV of "Continuous cover forestry" is the worst among all options (Table 2); the economically desirable features of this management option occur only in the far distant future. It is obvious that the advantages of "Continuous cover forestry" are "discounted away," even when assuming a DDR, while the adjustment to a discrete time Ramsey model does not have a major influence on the result. In addition, the ranking of the silvicultural options hardly changes by using DDRs compared to discounting with a constant 0.035 rate.

4.3.2. Theoretic example for considering the effect of optimized harvest operations

To conclude our analysis we will finally analyze the possible impact of omitting optimization when carrying out BCA of silvicultural options combined with DDR. We start with the conclusion by Davies and Kerr (2015, p. 2443) that "… scenario rankings remain relatively constant…", even under substantial changes of both, the level and the term structure of the discount rates. Given the usually enormous impact of the discount rate on the evaluation outcomes from BCA, this conclusion requires a closer look, because it is rather unexpected. Davies and Kerr (2015) pre-defined their management scenarios, so that no space is left for any adjustments (through optimization) of the investigated silvicultural systems in response to the assumptions made. It is common practice in comparative forest economics studies that management alternatives are specified more or less arbitrarily (Tahvonen and Rämö, 2016), which limits the conclusions about advantages or disadvantages of silvicultural management systems. In order to at least derive some tendencies about how the results may be impacted by such pre-definitions, we will here carry out simplified theoretical considerations to identify important drivers of economic return and outline possible implications of combining DDR with non-adjusted management practices.[1]

We use our own, artificially calculated data for the development of financial standing timber value (Fig. 3) and assume establishment costs of 1500 monetary units (mu) per hectare. New data was necessary to leave aside any pre-definitions in the original dataset by Davies and Kerr (2015). Our analysis compares a simple clearfell system without any thinnings with a stylized continuous cover system aiming at establishing five age cohorts covering 20% of the stand area each. We calculated the optimum (Faustmann) rotation when using a constant discount rate (CDR) of $r = 0.035$ (all considerations assume 5-year time steps) and when applying a DDR schedule based on a worst-case scenario for return on capital of 0.01.

Using DDRs complicates the exercise of finding an optimal rotation. As Price (2011) has shown, the rotation under DDR will lengthen and subsequent rotations will have an increasing yet unequal length. This result is built on dynamic consistency. One could argue that once the future has been achieved, it becomes the present and that this may require a revision of the rotation ages, seen from a new perspective. However, Price (2011) has shown that if the expected changes of circumstances which have led to the assumption of DDR are actually realized, no changes in the initially projected schedule of rotations will be made by new generations. We provide that the scenarios used to form the expected utilities in Eq. 7 are not altered from time to time. This means that our assumed DDRs would actually be applied consistently, without being revised by subsequent generations. For estimating the optimal rotation length for the clearfell system, we carry out an optimization over 1000 years using a nonlinear program.

In order to obtain a picture of the impact of DDR on optimization for the case of continuous cover forestry, we assume that the timing of the establishment of five age cohorts is the objective of our optimization. We provide that the removal of 20% of the timber for establishing an age cohort has an impact on the value growth of the remaining trees. We assume that over a 15-year period after such silvicultural operation, the value growth percentage of the remaining trees will increase by 0.75 percentage points if trees are younger than 50, by 0.5 percentage points if age is from 50 to 100, while beyond age 100 no increase is assumed. This is a plausible assumption, as usually silvicultural operations include the removal of trees with low value growth percentages, for example through harvesting trees with short crowns. Moreover, the increased space for the remaining trees will also support higher growth. Data published by Knoke and Plusczyk (2001) support these assumptions. In their study a 41-year old stand in transition to continuous cover forestry obtained a 0.75 percentage point higher volume growth over a 17-year period when compared with an even-aged stand, although this even-aged stand was with thinning. For an age of 58 the difference was 0.47 percentage points. Moreover, for each established age cohort we used the simplifying assumption that it would achieve the same net present value as calculated under the optimal sequence of rotations (adjustments presented in the results part), from the time of establishment onwards.

For the case of continuous cover forestry, using a multi-start option (50 restarts) was necessary to avoid local optima when solving the allocation problem. Finally we calibrated the growth of the newly established age cohorts under continuous cover forestry to estimate under which conditions both systems would achieve the same economic performance. This supported the analysis of factors that are responsible for the relative superiority of clearfelling vs. continuous cover forestry.

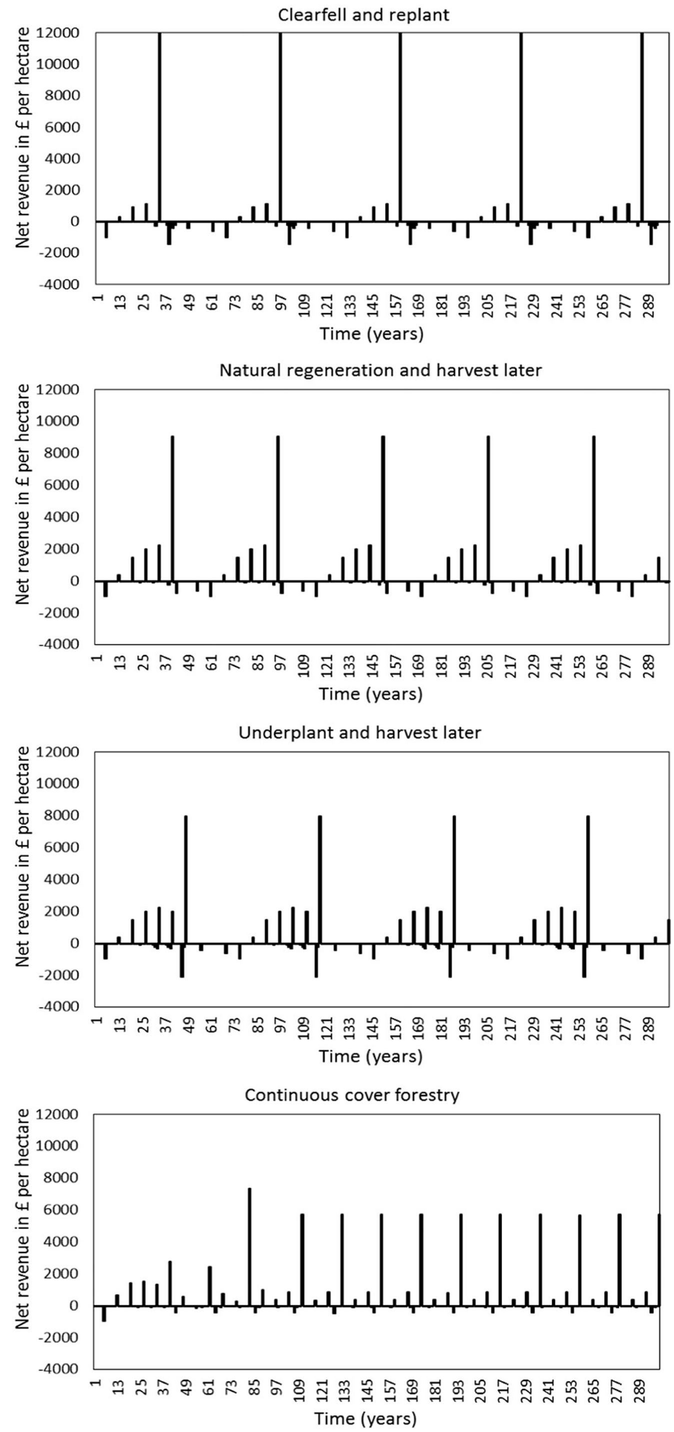

Fig. 2. Streams of cash flows for four forest management scenarios (adopted from Davies and Kerr, 2015). 300 years are depicted, while actually 1000 years have been considered, through repeating the same pattern of cash flows. Assuming 1000 years is considered to approach an "unlimited" time horizon.

5. Results and discussion

5.1. Impact of the marginality assumption

The assumption of marginality impacts the ranking of the silvicultural options. With increasing marginality of the forestry options, the

[1] We are grateful to two anonymous reviewers for their valuable suggestions.

Table 2
Basic financial data on forest management scenarios (adopted from Davies and Kerr, 2015); NPV is based on DDRs, starting with a 3.5% discount rate (until year 30), which declines to a discount rate of 1.0% from year 300 onwards (Fig. 1, Table 1).

Scenario	Net present value, NPV, declining discount rate (3.5%–1.0%)	NPV, declining discount rate, adjusted to a discrete time Ramsey model	NPV, constant discount rate (3.5%)	Sum of undiscounted cash flows over 1000 years
	[£/ha]			
S1 clearfell and replant	2852	2815	2559	110,028
S2 natural regeneration and harvest later	3027	2988	2554	168,119
S3 underplant and harvest later	1706	1681	1434	93,027
S4 continuous cover forestry	1568	1541	1024	223,850

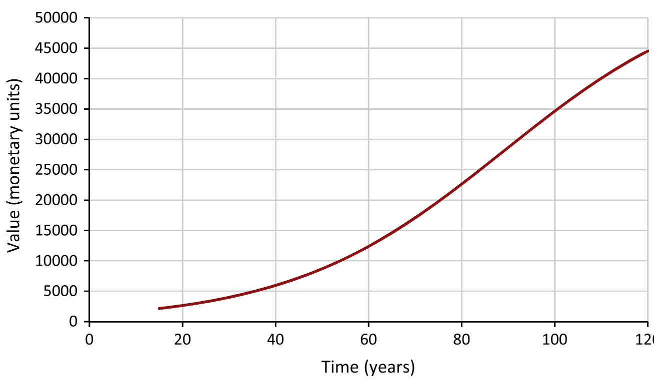

Fig. 3. Assumed development of standing timber value in monetary units.

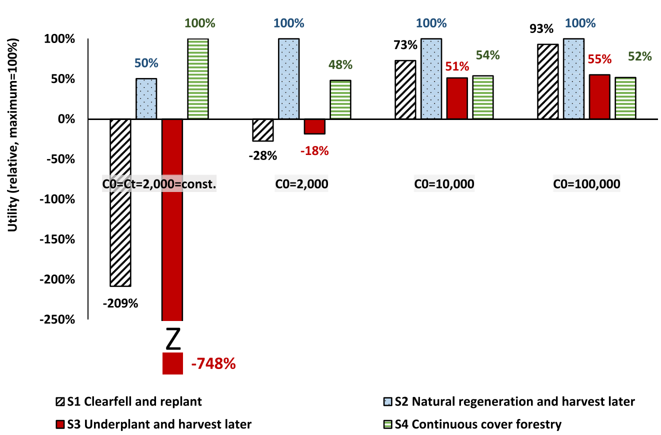

Fig. 4. Utility indices for four silvicultural options when assuming various flows of aggregate business-as-usual consumption, C_t. Utility indices are: $U_{index} = \frac{U_P}{U_{max}} \cdot 100$, where U_P is additional utility for a specific silvicultural option, P (Eq. 4). The bar for "Underplant and harvest later" with $C_0 = C_t = 2000$ = const. has been cut.

economic attractiveness of "Continuous cover forestry" decreases from being the best option to achieving just 52% of the maximum utility (Fig. 4). Fig. 4 assumes an aggregate business-as-usual consumption for Eq. 4, which is either constant (£ 2000/year) or growing. Thus, in a further variant, £ 2000/year is the start value, which subsequently increases at the rate of g_t according to Table 1. For these relatively small business-as-usual consumption flows, the forestry options are more than marginal regarding their contribution to consumption. When forestry is not marginal, "Continuous cover forestry" obtains the first or second rank. This is very different to the ranking obtained by Davies and Kerr (2015), who implicitly assumed marginality. In their study, "Continuous cover forestry" consistently achieved the worst ranked position. However, with increasing marginality, meaning an increasing size of the business-as-usual consumption flows, the ranking indicated by the utility indices in our study approaches the ranking based on discounted cash flows and with this the original ranking by Davies and Kerr (2015).

Higher and growing (with consumption growth rate) aggregate business-as-usual consumption of £10,000 or £100,000/year means that the consequences of the silvicultural options are marginal. Under this precondition, the utility-based rankings are identical with the rankings obtained by considering the NPV, with "Continuous cover forestry" in the last position. Remarkably, the option "Natural regeneration and harvest later" dominates not only the NPV-based ranking, but also the utility-based evaluation (with constant and small business-as-usual consumption being the only exception). This option combines low costs through natural regeneration with a more continuous distribution of cash flows than the conventional "Clearfell and replant".

5.2. Impact of the schedule of discount rates

5.2.1. Influence of worst-case scenarios on the return on capital

The minimum return on capital assumed for estimating the consumption-based discount rate (derived according to Eq. 7) has a major impact on the schedule of discount rates (Fig. 5). Consequently, the choice of the minimum possible return on capital is also influential for the resulting NPVs and, finally, for the ranking of the silvicultural options. While the position of the generally dominant option "Natural regeneration and harvest later" is relatively stable, that of "Continuous cover forestry" depends heavily on the assumptions made for the worst-case return on capital.

In general, we may say that the economic attractiveness of "Continuous cover forestry" increases with increasing precaution (expressed by including more pessimistic scenarios for return on capital). When including a very small or even zero return on capital "Continuous cover forestry" performs almost as good as ($r_{cap,wc} = 0.2\%$) or equally well ($r_{cap,wc} = 0\%$) as "Natural regeneration and harvest later" (Fig. 6).

We may conclude that the schedule for DDRs is of utmost importance. This schedule depends strongly on the chosen worst-case scenario for the return on capital.

5.2.1 Influence of increasing aversion against inequality.

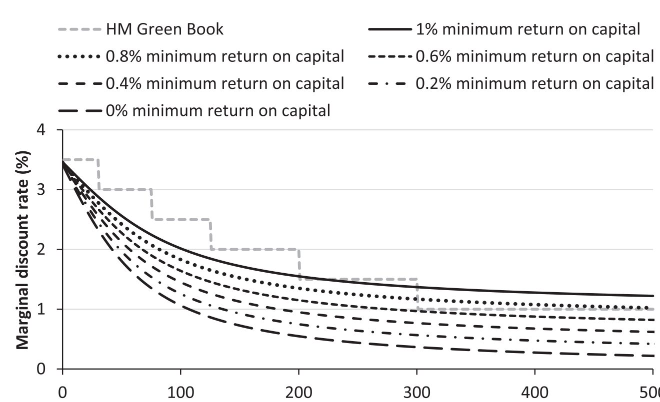

Fig. 5. Alternative DDRs derived by Eq. 7. Variation in the schedules of DDRs reflects different scenarios for the possible minimum return on capital.

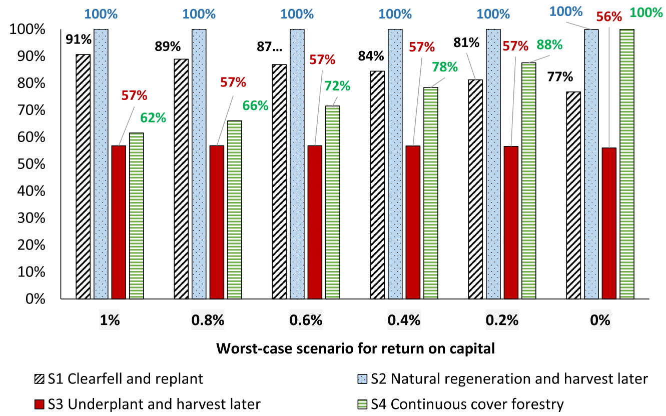

Fig. 6. Various NPVs derived with alternative DDRs (see Fig. 5), derived based on different assumptions about the worst-case return on capital invested in the economy.

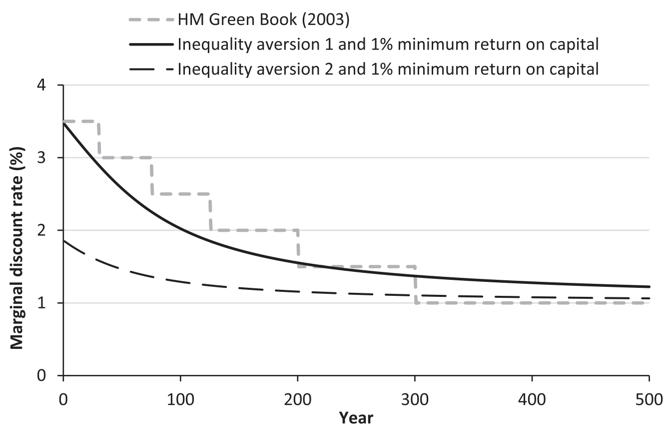

Fig. 7. Alternative DDRs derived by Eq. 7. Variation in the schedules of DDRs reflects different degrees of inequality aversion.

Increasing aversion against inequality is also an expression of higher risk aversion, because the coefficient, γ, which measures the curvature of the utility function, describes both characteristics. Therefore, an increasing aversion against inequality also means increasing precaution. The choice of γ has an important impact on the schedule of the DDRs, particularly on discount rates in the relatively near future (Fig. 7). Replacing the original $\gamma = 1$ by $\gamma = 2$ means that the schedule of DDRs becomes much flatter and the initial discount rate reduces by almost 50% compared to the original starting discount rate.

Greater aversion against inequality improves the competitiveness of "Continuous cover forestry" (Fig. 8). This option now achieves about 83% of the NPV for "Natural regeneration and harvest later". This underlines that increasing precaution would improve the position of "Continuous cover forestry," while "Natural regeneration and harvest later" remains dominant when assuming a higher aversion against inequality (if γ is smaller or equal 2). Consequently, the choice of the worst-case scenario for return on capital appears to have the strongest impact on the ranking of the silvicultural options, compared to the impact of increasing risk aversion.

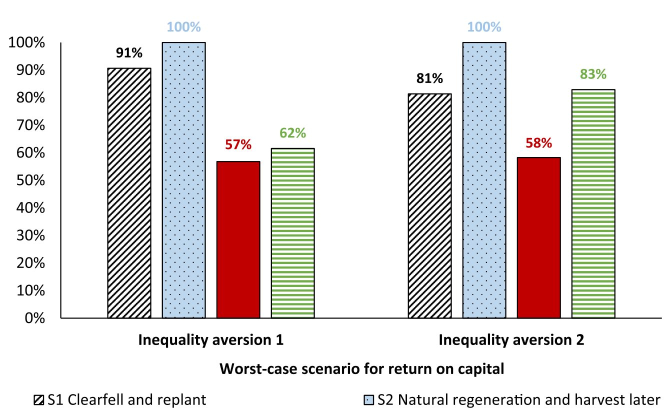

Fig. 8. Various NPVs derived with alternative DDRs (see Fig. 7), derived from different assumptions about the worst case return on capital invested in the economy.

5.3. *Theoretical impact of optimization*

5.3.1. *Optimization-based comparison*

Using our artificial dataset (Fig. 3), and a clearfell strategy, we obtained a constant optimum (Faustmann) rotation period of 60 years when applying a constant discount rate (CDR of $r = 0.035$). Introducing a DDR schedule we obtained optimal rotation ages of 85 (first rotation), 90 (second rotation), and then constantly 95 years for all subsequent rotations, which means a substantial increase in rotation lengths under DDR in our example. This dynamic of the optimal rotation length has been disregarded in Davies and Kerr (2015), who used constant and substantially shorter rotation periods.

For the continuous cover forestry scenario, a CDR of $r = 0.035$ resulted in an optimal establishment time for the first age cohort already at age 20 (which accelerates the growth of the relatively young remaining trees). The optimal establishment time for the second age cohort was 35, and for the third 60; the felling of the last trees of the initial stand was simulated at age 70 to establish the fourth and fifth age cohort at the same time (Table 3).

This continuous cover system starts establishing an age cohorts very early and subsequent age cohorts periodically, with 15 to 20 years distance, which would not be too far from a suggested practice of transitioning to continuous cover forestry (e.g. Knoke and Plusczyk, 2001). In contrast to the case of using CDRs, applying DDRs would postpone all silvicultural activities. Under this scenario, we obtained a later optimal establishment time for the first age cohort at age 30 and for the second age cohort establishment was optimal 35 years later, at age 65. Age cohorts three (age 80), four and five (age 95 both) would follow under optimality with a time distance of 20 and 15 years. Consequently, the obtained harvesting cycles are more typical for continuous cover forestry when CDRs are applied compared to using DDRs.

However, both examples show implicitly that irregular management is economically attractive under our assumptions, which provide that silvicultural operations accelerate the growth of remaining trees, but also that age cohorts in the continuous cover forests grow as profitably as under the clearfelling system. If the clearfelling system would have been superior under these assumptions, the model would have suggested establishing all age cohorts at the same, optimal start rotation period (either 60 or 85).

The reported results do not mean that continuous cover forestry is actually superior to the clearfelling system from an economic point of view. We need to consider that the established age cohorts in the

Table 3
Optimization of the time to establish age cohorts under continuous cover forestry.

	Time to establish an age-cohort [year]	
	Declining discount rates (DDR $r_t = 0.035 \ldots 0.010$)	Constant discount rates (CDR $r = 0.035$)
Age cohort #	Optimal establishment at stand age	
1	30	20
2	65	35
3	80	55
4	95	70
5	95	70
Net present value	2020 monetary units	308 monetary units

Table 4
Consequences of applying declining discount rates (DDR, from 0.035 down to 0.01) for cases when it is appropriate and when it is not. CDR means constant discount rates. 1687 monetary units/ha is a start value for the NPV of both systems, obtained through calibration, i.e. through reducing the NPV of age cohorts in continuous cover forestry until an NPV of 1687 (that of the clearfell system) was achieved.

Term structure used for optimization	Net present value [monetary units, mu, per hectare]			
	DDR is true		CDR is true	
	Continuous cover forestry	Clearfell system	Continuous cover forestry	Clearfell system
DDR applied	1687		22	− 70
CDR applied	1294	1339	186	83

continuous cover system will show only reduced increment and will also have other economic disadvantages (e.g. more expensive harvesting), as they grow up partly under the canopy of older trees. Given this background, we reduced the NPV of the five age cohorts until the same economic performance level as for the clearfelling system was achieved (Table 4). This calibration resulted a possible reduction of ∼34% until the total NPV for the continuous cover treatment became equal or lower than the NPV of the clearfelling system. This means that in the case of DDRs the clearfelling system will be superior, if the NPV of age cohorts established under the continuous cover system reduces > 34% compared to the NPV of the clearfelling system.

For the case of applying CDRs, we could reduce the NPV of the age cohorts even by 73% and still the economic performance of the continuous cover system was equal to that of the clearfelling system. This supports the conclusion that (optimized) continuous cover systems appear to be even more attractive under CDRs. This is consistent with existing evidence. The relative economic performance of continuous cover forestry compared to clearfelling systems tends to improve with increasing discount rates (Chang, 1981, Tahvonen et al., 2010, Tahvonen and Rämö, 2016).

Starting for both silvicultural systems with the identical NPV (i.e. 1687 monetary units, mu, per hectare) achieved through calibration, our analysis reveals a significant sensitivity of both silvicultural management systems when ignoring optimization and following pre-defined not adapted management schedules. For example, when management schedules derived from analyses under CDRs were evaluated with DDRs the NPV of the clearfelling system drops from 1687 to 1339, and the NPV of continuous cover forestry falls with 1294 mu/ha to a similar value. If the optimal sequence of rotations under DDR (first 85, second 90, and then 95 years for all subsequent rotations) was evaluated by means CDRs, the NPV of the clearfelling system drops into the negative area, while + 83 mu/ha would be possible under the optimal schedule, which would follow a constant 60-year rotation (Table 4). The NPV of continuous cover forestry dropped from 186 (optimized with CDR) to + 22 mu/ha (optimized under DDRs), if CDRs rather than DDRs would actually be appropriate. In conclusion, our considerations suggest a significant sensitivity of both systems to deviations from the optimality assumptions, i.e. when using pre-defined management scenarios.

5.3.2. *Important factors driving relative economic performance*

Our exercise followed a simplified approach, but some aspects have become obvious which might explain the obtained differences in our results when compared to those published by Davies and Kerr (2015). In their study, the performance of continuous cover forestry has consistently been very poor under all variations tested. However, our example has shown that the acceleration of the growth of the remaining trees by means of silvicultural operations is exceptionally important. If we eliminate this effect from our optimization, the silvicultural system switches automatically towards clearfelling, suggesting the previously obtained sequence of optimal rotations. Consequently, modeling the biological tree response to silvicultural operations appropriately is extremely important. In addition, the prediction of the growth of young age cohorts in continuous cover forests is an important factor. In this context it may be a limitation if stand level growth modeling needs to be applied, which cannot capture the growth response of individual trees in irregular silviculture (Davies and Kerr, 2015, p. 2431). Another crucial point is when to start with transitioning to continuous cover forestry. Our simplified considerations suggest that this should be fairly early (age 30 or even 20). However, the continuous cover scenario in Davies and Kerr (2015, p. 2430) simulates the first regeneration harvest (associated with a removal of 20% of the stand's timber) only at age 65. This is beyond the rotation age in the classical clearfelling scenario and economic gains are, thus, quite unlikely – rather the opposite will be the case from the point of view of economic efficiency.

6. Perspectives and implications

Our investigations for applying BCA to forest management decisions demonstrate the importance of the theoretical economic perspective chosen for valuation. The economic perspective and the way to design management alternatives may have much stronger impact on the results of BCA than changes in the coefficients of the BCA. For example, Davies and Kerr (2015) investigated changes in overhead and management costs, timber prices or discount rates, to check the robustness of the results, but did not find a great impact on the ranking of silvicultural options. According to our findings, their sensitivity studies do not necessarily support high robustness of the results obtained by Davies and Kerr (2015).

From a forest policy point of view the study by Davies and Kerr (2015) is hardly able to generally distract from continuous cover forestry. First, it is important to note that the analysis based on the HM Green Book (2003) may only hold for public forestry and only if forest management contributes marginally to the business-as-usual consumption of an economy. This precludes transferring the results of Davies and Kerr (2015) to examples of private forestry, where private forestry represents about 70% of the British forest area. Moreover, for the countries where the forest sector contributes more than marginally to the gross domestic product (GDP) one should consider using the discounted utility approach instead of the standard discounted cash flow approach for BCA. For example, in Finland the forest sector contributed 4.8% to the GDP in 2010 (Metla, 2012); in some regions this contribution was almost 14%.

In private forestry, the economic consequences of changing the silvicultural method may be non-marginal, if forest owners with large properties obtain most of their income from forestry activities. Such a situation would warrant applying the discounted utility rather than the discounted cash flow approach. Even if a transition towards an alternative silvicultural strategy may only be carried out on a limited area each year, after a certain period the whole forest will be restructured. The impact of this process on the annual stream of cash flows may be non-marginal. However, the question of whether forestry is marginal or not also depends on the other assets of a forest owner; for example, some forest owners will also be involved in agriculture or other profitable activities. Non-marginality will only be the case if forestry is the dominant activity of the forest owner.

The scientific contributions of applying DDR are so far mostly limited to public project evaluation and, thus, to the case of applying a social and not a private discount rate. Selecting a private discount rate can be a more straightforward task, at least if the far distant future is not concerned. Theoretically, an appropriate private discount rate could be based on the opportunity cost of the forest company, derived by the weighted average cost of capital or by estimating capital costs based on the capital asset pricing model. However, as Hepburn and Koundouri (2007) confirm, the theory on uncertainty in future economic return or consumption growth rates applies with equal force to the certainty-equivalent discount rate for the private sector.

In addition, support for declining discount rates in the private forestry sector is provided, for example, by Ducla-Soares et al. (2001, p. 3). Their study points out that "… the use of decreasing discount rates may contribute to a better understanding of the decision making process that characterizes private forest owners. Often, we observe that forest owners do not behave as expected when anticipating the cutting time, and, thus frustrate the predictions of the Faustmann model based on constant discounting."

Another conclusion supported by our study is that using DDRs should imply analyses about the sensitivity of the results to variations in the DDR schedule. This is of highest importance; Freeman and Groom (2016) confirm that possible bounds for upper and lower levels of the (declining) social discount rate "… are widely spread for horizons beyond 75 years …". Carrying out sound sensitivity studies includes making the assumptions behind the schedule of DDRs explicit. In particular, close attention should be paid to the worst-case return on capital.

Such analyses of the theoretical background of BCA provide interesting insights and call for a very cautious interpretation of the rankings of silvicultural options obtained with discounted cash flow methods under DDRs. In addition, the silvicultural assumptions made may also have a very great impact. Price (2011) and our theoretical considerations have shown that DDR would lead to successive rotations of various lengths. The continuous cover option has also not been optimized in Davies and Kerr (2015), which may be a significant limitation, as shown by our theoretical exercise. Sophisticated single-tree-based optimization methods coupled with advanced growth modeling point in a similar direction. Often such sophisticated approaches will implicitly lead to continuous cover forestry (e.g. Tahvonen et al., 2010; Tahvonen and Rämö, 2016), even if maximization of discounted cash flows forms the objective function. Another study by Jacobsen et al. (2016) confirmed the superiority of continuous cover over clearfelling systems, based on their better area usage. Jacobsen et al. (2016) derived ambiguous theoretical results concerning the rotation length of age cohorts in a continuous cover system and under clearfelling. However, on a numerical basis Jacobsen et al. (2016) demonstrated longer rotation periods for continuous cover than for clearfelling systems, if the forest area is unconstrained. We don't expect that their results would change much when applying DDRs. The main effect investigated by Jacobsen et al. (2016) is a more efficient area utilization of the continuous cover system, which occurs from the beginning of their investigation where two fully regulated systems (forests in an equilibrium) have been compared. One could expect that applying DDRs would increase the net present value of both systems and, at the same time, would expand rotation periods in both systems. However, given our results, rotation periods would change over time so that the equilibrium forest structure would also change over time, in both systems. Still one has to keep in mind that our study has considered the transition from a clearfelling to a continuous cover system and not both forestry systems in an equilibrium. Consequently, it is hard to make a direct comparison.

Our study confirms high sensitivity of the results to the assumed schedule of DDRs. Such DDRs may result either from expert opinions (e.g. Weitzman, 2001), econometric analyses (e.g. Newell and Pizer, 2003), or from a normative selection of parameters determining the DDR, an approach we tested in our study. Concerning expert opinions, Freeman and Groom (2014) raise some important issues. Expert opinions may vary for quite different reasons, which mean that discount rates may decline rapidly, or the term structure can be much flatter, if new experts provide additional information.

The alternatives to using expert opinion also do not lead to a consensus about the desirable schedule of DDRs. Based on extensive analyses of published data and proposals made for DDRs, Freeman and Groom (2016) present a depressing finding for practitioners of BCA. They conclude "… that estimated present values are likely to be so imprecise as to provide only minimal guidance to policy makers on intergenerational projects." Evaluations cannot even be sure of whether or not the term structure of discount rates will always decline. Based on the capital asset pricing model, Gollier (2012) argued that discount rates should increase over time for projects, for example to mitigate climate change, which have a high beta factor[2] (and are not marginal). Obtaining a private investor's perspective, Kruschwitz's (2009) replication portfolio method supports a flat or slightly increasing term structure of discount rates, but only when considering a period of up to 30 years.[3] Given the extremely high variation of DDRs with either a potentially flat or even increasing term structure of discount rates, we can only support the broader conclusion by Freeman and Groom (2016) that we have to search for additional criteria to support intergenerational decision-making. One could follow, for example, Chichilnisky's (1997) approach to sustainable resource management, which considers benefits related to the existence of the resource stock in addition to benefits from consumption. We could summarize such benefits under the term "ecosystem services". It would certainly be important to incorporate such benefits into the evaluation of public forestry and other environmental projects. An example for such an approach is Baumgärtner et al. (2015), who considered growth or decline in manufactured consumption goods and in ecosystem services for deriving appropriate and different discount rates. However, good-specific declining discount rates would probably not lead to a better consensus about the desirable schedule of discount rates as their derivation would become even more complicated. Alternative approaches to consider ecosystem services include either using economic value coefficients in land-use modeling (Kindu et al., 2016) and optimization (Bateman et al., 2013), or integration of normalized indicators for ecosystem services into multi-criteria optimization of land use (Knoke et al., 2016).

7. Concluding remarks

In conclusion, the opportunity to adopt DDRs is associated with a number of assumptions, which complicate the valuation of long-term projects and may even increase the variability of the results. Consequently, using DDRs requires a high degree of care and quite knowledgeable evaluators. If DDRs enter BCA of forestry options, it is crucial to justify their term structure, to carry out sensitivity studies and to integrate optimization approaches. In addition, BCA in forestry should generally consider whether the marginality assumption is justified. Alternative approaches to sustainability, such as acknowledging economic benefits from the existing natural stocks represented by the ecosystems instead of still focusing on consumption only, may also be promising. This means that future forest economic research about silvicultural management options has high potential for further development.

Acknowledgements

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[2] The beta factor indicates how the returns of a project vary in relation to the market portfolio. A beta > 1 means that the project returns are more variable than those of the market portfolio, while the project returns correlate positively with the market returns.

[3] Kruschwitz (2009) mentions other limitations of this method, which include that short sales are necessary to replicate the cash flows of the evaluated asset. However, legal regulations may limit the opportunities for short sales.

Appendix A. Appendix A

Proof 1. We use the identity $\left(\frac{1}{1+r_t}\right)^t = \frac{U'(C_t)}{U'(C_0)}\left(\frac{1}{1+\rho}\right)^t$ (Gollier, 2010; Weitzman, 2012; Dietz and Hepburn, 2013), to substitute the consumption discount factor, $\left(\frac{1}{1+r_t}\right)^t$, and get $\sum_{t=0}^{\infty} \Delta_t \frac{U'(C_t)}{U'(C_0)}\left(\frac{1}{1+\rho}\right)^t$. We replace $\Delta_t U'(C_t)$ by $U(C_t + \Delta_t) - U(C_t)$ and obtain:

$$\frac{1}{U'(C_0)} \sum_{t=1}^{\infty} [U(C_t + \Delta_t) - U(C_t)]\left(\frac{1}{1+\rho}\right)^t$$

This confirms that maximizing the sum of discounted cash flows will also maximize the sum of discounted utilities, if cash flows, Δ_t, are marginal. $\frac{1}{U'(C_0)} > 0$ and has no impact on the ranking of the projects, as it is the same for each evaluated project. This means that projects may usually be evaluated by means of the marginal utility of the aggregated business-as-usual consumption stream, if their impact is small enough, which allows using discounted cash flows instead of discounted utilities, if the consumptions discount rate is appropriately chosen (see below).

Appendix B

Proof 2. Given $U'(C) = C^{-\gamma}$ as marginal utility and γ as the coefficient of constant relative risk aversion we have: $r_t = exp\left(-\frac{1}{t}[\,lnE\widetilde{C}_t^{-\gamma} - lnE\widetilde{C}_0^{-\gamma}] + ln(1+\rho)\right) - 1.$

Using $\frac{lnE\widetilde{C}_t - lnE\widetilde{C}_0}{t} = ln(1 + g_t)$, with g_t being the uncertain consumption growth derived from uncertain aggregated business-as-usual consumption streams, we get $r_t = \exp(\gamma \ln(1 + g_t) + \ln(1 + \rho)) - 1$ and $\ln(1 + r_t) = \ln(1 + \rho) + \gamma \ln(1 + g_t)$. This is consistent with the original Ramsey formula, $r_t = \rho + \gamma g_t$, which is in continuous time.

Appendix C

Gollier's (2010) basic assumption about flexible consumption plans means that consumption is conditional to the expected return on capital invested into the economy (e.g. Cromb and Fernandez-Corugedo, 2004). Such interdependency between consumption and return on capital becomes theoretically evident when considering the optimal consumption path (Gollier, 2010). Our argument presented follows Gollier (2010) but is illustrated for the case of discrete time, while Gollier provided continuous time.

Given that information on the return on capital r_{cap} is available, reducing initial consumption at time t_0 by Δ leads to increased consumption at time t_1, which has the size: $\Delta(1 + r_{cap})^{(t_1} - t_0)$. Consequently, the optimal consumption path implies that $\Delta\, U'(C_{t0})$ is equal to: $\Delta(1 + r_{\text{cap}})^{(t_1 - t_0)}(1 + \rho)^{-(t_1 - t_0)} U'(C_{t1})$. Given a specific r_{cap}, we achieve optimal consumption over time as:

$$U'(C_0) = \left(\frac{1 + r_{cap}}{1 + \rho}\right)^t U'(C_t) \tag{A1}$$

However, information about consumption is uncertain, meaning that in practice we have $\widetilde{C}_0$ instead of C_0, and $\widetilde{C}_t$ instead of C_t (and $\widetilde{r_{cap}}$ instead of r_{cap}). This implies using expected values to derive utility. If we assume a frictionless economy, we may replace r_{cap} in Eq. A1 by r_t and the consumption-based discount factor would then be (in discrete time):

$$(1 + r_t)^{-t} = \frac{EU'(\widetilde{C}_t)}{EU'(\widetilde{C}_0)}(1 + \rho)^{-t} \tag{A2}$$

which leads us to Eq. 7, main text.

The optimal consumption growth that fulfills the optimality condition (Eq. A1) is:

$$ln(1 + g_t) = \frac{ln(1 + r_t) - ln(1 + \rho)}{\gamma} \tag{A3}$$

When deriving the desirable schedule of discount rates, we can now assume scenarios, i, for consumption that is associated with a specific probability, w_i. We assume for each $C_{t,i}$ that: $C_{t,i} = C_{0,i}(1 + g_{t,i})^t$. For each $C_{0,i}$ we require: $C_{0,i} = \left(\frac{1 + r_{cap,i}}{1 + g_{t,i}}\right) - 1$ and for the optimal $g_{t,i}$ we need: $g_{t,i} = \left(\frac{1 + r_{cap,i}}{1+\rho}\right)^{\frac{1}{\gamma}} - 1$ (what follows from Eq. A3). $C_{0,i}$ is the fraction of wealth consumed at time 0 (Cromb and Fernandez-Corugedo, 2004) depending on the assumed return on capital for scenario i, $r_{cap,i}$, but adjusted for the associated optimal growth of consumption, $g_{t,i}$, which consumers should select under scenario i.

It is evident that under these assumptions the consumption path strongly depends on the return on capital invested in the economy. Moreover, the forecasted term structure of discount rates is here decreasing over time when future discount rates are positively correlated, which means that there is a high chance of having long periods of persistently low discount rates (Arrow et al., 2013).

Once we have obtained the schedule of DDRs (sequence of r_t over time), Eq. A4 will result in the appropriate NPV for each project.

$$NPV_{p,DDR} = \sum_{t=0}^{\infty} \Delta_t\, d_t$$

with:

$$d_t = \prod_{z=1}^{t} \frac{1}{1 + r_t} \tag{A4}$$

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