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Methodological and Ideological Options

Social Cost of Forcing: A Basis for Pricing All Forcing Agents

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ABSTRACT

An efficient climate policy is based on cost-benefit analysis (CBA) and equates marginal abatement costs across all forcing agents affecting climate change. In CBA, the agents' contributions to radiative forcing (RF) must be consistently priced (i.e. the social cost of RF, occurring at a specific time, must be the same regardless of the agent causing it). We present a concept that enables doing so. The Social Cost of Forcing (SCF) is the monetary value of the social damage caused by marginal RF at a given instant (Wm^{-2}). Any forcing agent whose temporal decay profile and radiative efficiency are known can be priced based on it. Prices obtained for distinct agents are consistent in CBA, as long as the same SCF and discounting assumptions are applied. Hence, the SCF is a concise way to communicate social cost information: mutually consistent prices for any set of forcing agents can be obtained based on a single Integrated Assessment Model output, the SCF. We explain the theoretical foundations of the concept and illustrate its practical applications with two examples: (1) we derive SCF-based prices for CO_2 and CH_4, and (2) we estimate the social cost of albedo changes in a boreal forest stand.

1. Introduction

Humans alter Earth's energy budget by changing the absorption and reflectance of solar radiation through various mechanisms, e.g. changing the atmospheric concentrations of greenhouse gasses (GHGs) and modifying Earth's surface albedo (IPCC, 2013). Each mechanism is associated with a particular set of forcing agents[1] (hereafter *forcers*) that affect the climate (for example, GHGs or aerosols). Radiative forcing[2] (RF) is a standard measure for quantifying the warming (or cooling) effects of distinct forcers. Increased atmospheric CO_2 is the largest individual source of anthropogenic RF. However, also numerous other forcers contribute to climate change (Myhre et al., 2013). Efficient climate policy should therefore optimally regulate all forcers, rather than CO_2 only (van Vuuren et al., 2006). This is recognized in international climate agreements that e.g. require the accounting of various non-CO_2 GHGs (UN, 1992, 1998, 2015). Another key aspect of efficient climate policy is optimizing the timing of mitigation measures, which is a form of economic cost-benefit analysis (CBA): mitigation costs are weighed against the benefit of avoided climate damage (e.g. Nordhaus (1992, 2014)). When the costs and benefits of public projects are analyzed, the adverse impact of CO_2 emissions can be included by pricing the emissions according to the Social Cost of Carbon (SCC) (e.g. Pizer et al., 2014). Including other forcers in such analyses requires consistent measurement and valuation of their harmfulness; climate damage of equal proportion, occurring at the same time, must be equally valued, regardless of the forcer causing it. In this study we show how all forcers can be priced consistently based on a single fundamental price: the Social Cost of Forcing (SCF). We generalize and analyze the method previously proposed for pricing albedo by Lutz and Howarth (2014).

Forcers can be divided to two main types: *pulse forcers* and *transient forcers.*[3] Pulse forcers are emitted into the atmosphere and contribute to RF during their lifespan therein. That lifespan may be long or short. Thus, pulse forcers include long-lived well-mixed GHGs, such as CO_2, but also short-lived pollutants (near-term climate forcers), such as aerosols. Transient forcers, on the contrary, have only instantaneous effects. For example, the instantaneous warming impact of surface albedo, depends on the state of the planetary surface at that specific moment. Another example of a transient forcer is the anthropogenic heat flux from combustion. Notably, some forcers may be hybrids of the two

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[1] Elsewhere in literature 'forcing agents' are also referred to as 'climate agents' and 'forcings'. We prefer the shorter term 'forcer'.

[2] Throughout the manuscript the term 'radiative forcing' (RF) is used to refer to 'effective radiative forcing' (ERF) as it is defined in Myhre et al. (2013) as the "change in net downward radiative flux at the top of the atmosphere (TOA) after allowing for atmospheric temperatures, water vapour, clouds and land albedo to adjust, but with global mean surface temperature or ocean and sea ice conditions unchanged". Notably, this differs from the usual definition of RF. If the usual definition is applied, an equal amount of RF caused by distinct forcers may lead to climatic impacts of different magnitudes. However, equal ERF leads to more uniform climate sensitivity across forcers. The importance of uniform climate sensitivity is discussed in Section 2.1. The difference between RF and ERF is discussed in detail in Myhre et al. (2013).

[3] Note that this typology differs from the conventional division of forcers to short- and long-lived forcing agents, applied in e.g. Shine et al. (2007). In our terminology, short- and long-lived forcing agents are both pulse forcers (whose atmospheric lifespans differ). Only forcers with truly instantaneous impacts are considered 'transient forcers'.

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main types; black carbon is a pulse forcer (aerosol) in the atmosphere but becomes a transient forcer (i.e. affects surface albedo) when deposited on snow (Ramanathan and Carmichael, 2008).

Global Warming Potential (GWP) (Lashof and Ahuja, 1990) is perhaps the best known metric for measuring relative climatic impacts of pulse forcers. The Absolute Global Warming Potential (AGWP) of a pulse forcer is the time-integrated radiative forcing caused by a 1 ton pulse, emitted today, over a given timespan (e.g. 20, 100 or 500 years). The GWP of a forcer is the ratio of its AGWP to that of CO_2. For example, the GWP_{100} of fossil methane is 30 (Myhre et al., 2013), which means that the over a hundred year timespan a ton of methane emitted today causes cumulatively 30 times more RF than a ton of CO_2. Due to the popularity of the GWP as a metric for pulse forcers, some attempts have also been made to derive GWP values for transient forcers (see e.g. Bright et al., 2011 or Allen et al., 2016). Global Temperature Potential (GTP) (Shine et al., 2005) is another commonly used metric for comparing forcers. The Absolute Global Temperature Potential (AGTP) of a forcer is the change in global mean surface temperature at a chosen point in time in response to a 1 ton pulse emitted today. The GTP of a forcer is the ratio of its AGTP to that of CO_2.

As metrics such as GWP and GTP are readily available, one might consider applying them to derive relative prices for different forcers (e.g. if the carbon price were known, one might attempt to obtain a price for methane by multiplying the carbon price by methane's GWP).[4] Unfortunately, this approach produces prices that are not consistent in cost-benefit analysis (CBA). The socially optimal price of an externality (in this case a specific climatic impact caused by an economic activity) should reflect its social value (e.g. Pigou, 1932). For example, the Social Cost of Carbon (SCC) is defined as the present value of the damage caused by a 1 tonne CO_2 emission pulse over its lifespan in the atmosphere (see e.g. Pearce, 2003 or Pizer et al., 2014). However, AGWP and AGTP are purely physical metrics: AGWP measures cumulative RF, AGTP measures the lagged temperature response to RF. Neither measures damage nor includes the regulator's time preference. As the present value of the damage caused by the emission pulse does not necessarily depend linearly on RF or warming, GWP and GTP do not indicate the ratio of the damage caused by different forcers[5] (Eckaus, 1992, Schmalensee, 1993). Thus, they cannot be –a priori– assumed suitable for expressing the relative prices of different forcers. The link between GWP, GTP and economic damage metrics is discussed in more detail in Tol et al. (2012).

In this study, we show that there is a fundamental price, the SCF, which can be used to value pulse forcers and transient forcers alike. The SCF is the social value of the damage caused by a marginal unit of RF (Wm^{-2}) at a specific point in time. If a discount rate is chosen and the resulting time trajectory of the SCF is known, a unit price (social cost) for any forcer can be calculated based on the temporal profile of its contribution to RF. Shadow prices derived in this manner for distinct forcers are mutually consistent, if the same SCF and discounting assumptions are applied across the board. Previously, such an approach has been applied by Lutz and Howarth (2014) to derive a shadow price for the warming impact of forest albedo (i.e. a price that is consistent with the shadow price of carbon obtained from the DICE model). We expand upon their work in two ways. First, while Lutz and Howarth (2014) focus on pricing a specific (transient) forcer, i.e. albedo, we show how the method can be flexibly applied to pricing all forcers regardless of their type (pulse, transient or hybrid) and, therefore, the method has broad applications whenever there is a need to include the social value of climatic impacts in CBA. Second, while Lutz and Howarth (2014) explain their method in the context of a specific Integrated Assessment Model, i.e. DICE (Nordhaus, 1992, 2014), we generalize this explanation by deriving our results (i.e. explaining the SCF concept and showing the structure of forcers' prices) using a general model which embodies the basic characteristics of Integrated Assessment Models (IAMs) in which economic growth is endogenous and optimal climate change mitigation over time is based on economic cost-benefit-analysis.[6] These results are presented in Section 2.

In Sections 3 and 4 we provide numerical examples of pricing forcers based on the SCF. The SCF trajectory utilized in the examples is derived using the DICE2013R model.[7] Our first example illustrates the pricing of pulse forcers. We calculate prices for carbon (SCC) and methane (SCM) based on formulae derived in Section 2. We demonstrate how these prices vary depending on assumptions made about discounting. Our second example illustrates the pricing of a transient forcer, namely forest albedo. As albedo pricing has been previously considered by Lutz and Howarth (2014) in the case of the White Mountain National Forest (WMNF) in New Hampshire, USA, for a change we provide our example in a different geographical context. We simulate the development of the albedo of a Norway Spruce (*Picea abies*) stand in Southern Finland over a 66 year rotation and calculate the annual social cost of the albedo-induced warming effect of the (changing) tree cover.

The idea of deriving socially optimal shadow prices for forcers is not new. Previously, prices have been derived for pulse forcers, such as carbon (see Tol (2011) for a review) and methane (Hope, 2005, Hope, 2006), as well as at least one transient forcer, i.e. forest albedo (Lutz and Howarth, 2014). However, what is new is the way in which these prices are derived. Previously, the prices have been derived directly using IAMs. We show how they can be derived from a single IAM output: the SCF. This approach is useful, as it offers a concise way to communicate information between economists (who estimate the social cost of RF) and end-users (who wish to apply shadow pricing to a broad range of forcers in cost-benefit analyses which include the social value of climatic impacts). Notably, the economists working with IAMs do not know the full range applications that individual end-users have in mind. Therefore, they cannot publish an exhaustive list of consistent prices for all forcers. Likewise, the end-users are often not experts in integrated assessment modelling who would be capable of modifying an IAM to derive the set of shadow prices required by their specific case study. However, given an SCF trajectory, they can flexibly price any forcer they wish. The objective of this article is to explain the broad possibilities of the applying this approach.

Notably, similar information cannot be efficiently communicated by publishing the time trajectory of the social cost of a specific pulse forcer, such as CO_2. While the SCF is a ‘fundamental price’ that provides a basis for pricing all forcers, the same cannot be done based on the SCC because traditional climate metrics cannot be used to consistently convert the carbon price to prices for other forcers. To illustrate this point, we present the concept of Social Cost Ratio (SCR), which is the ratio of the unit social cost of a given forcer to that of CO_2 (Section 2). A similar concept has been previously discussed by e.g. Tol et al. (2012). In a numerical example, we compare the SCR and GWP for methane (Sections 3 and 4) and argue that, as the two metrics differ, a consistent price for methane cannot be derived by multiplying SCC by the GWP for methane. Pricing pulse forcers, such as methane, based on the SCF is a better option. Alternatively, if the CO_2 price is used as a benchmark, a price for methane can be obtained by multiplying the SCC by the SCR of methane.

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[4] Indeed such conversions are common: e.g. the EU emission trading system relies on GWP-values in when converting N_2O emissions into CO_2 equivalents (European Commission, 2012). Also, numerous studies have considered the impact of the choice of metric on abatement costs (e.g. Smith et al. (2013), Reisinger et al. (2013), van den Berg et al. (2015), and Harmsen et al. (2016)).

[5] As the GTP was not invented until 2005, Eckaus (1992) and Schmalensee (1993) discuss only GWP. However, the same critique applies to the GTP.

[6] In this article, the term IAM specifically refers to this particular type of models and not IAMs in a more general context.

[7] Notably, although our numerical examples utilize the DICE2013R model, the theoretical content of the study is independent of the choice of IAM.

2. Theory and Concepts

2.1. Climate Model

We follow Hasselmann et al. (1993), Boucher and Reddy (2008) and Olivié et al. (2012) and present the current global mean temperature change $T(t)$ in kelvins (K) as a convolution of a history of radiative forcing, $F(t)$, measured in Wm^{-2}, and impulse response of temperature to transient unit forcing (a Green's function), $\varphi(s)$, measured in $\mathrm{K}(\mathrm{Wm}^{-2}\,\mathrm{yr})^{-1}$, as[8]

$$T(t) = \int_{-\infty}^{t} F(s)\varphi(t-s)ds. \tag{1}$$

The temperature change in response to RF is usually approximated using data from atmosphere-ocean general circulation models.

Pulse forcers and transient forcers cause RF through different mechanisms. The RF of pulse forcers is determined by their atmospheric mixing-ratio, or equivalently, by the mass of their atmospheric stocks $S_i(t)$. As the absorption bands may overlap (as in the case on CH_4 and N_2O) the total RF caused by all pulse forcers (together) is best summarized by a function $F_P(\boldsymbol{S}(t))$ which allows for interactions between separate forcers. The RF caused by transient forcers, $\boldsymbol{X}(t)$, is a result of direct actions, such as input use in energy generation (which affects the anthropogenic heat flux) or the allocation of land to different uses (which affects surface). The total transient forcing is $F_T(\boldsymbol{X}(t))$. The total RF, $F(t)$, is a sum of contributions by pulse forcers and transient forcers, i.e.

$$F(t) = F_P(\boldsymbol{S}(t)) + F_T(\boldsymbol{X}(t)). \tag{2}$$

The direct summation of distinct forcers' impacts and their utilization in (1) requires that all forcers have efficacies (Hansen et al., 2005) close to unity. This requirement is satisfied when effective radiative forcing (ERF) is used as a measure of forcing (Myhre et al., 2013).

We model the dynamics of atmospheric pollutant stocks in the same way as we model global temperature change (1). The net flow of emissions, $E_i(t)$, measured in tyr^{-1}, feeds into the pollutant stock, $S_i(t)$, measured in tons. We obtain the expression

$$S_i(t) = \int_{-\infty}^{t} E_i(s)\varepsilon_i(t-s)ds, \tag{3}$$

where the function $\varepsilon_i(s)$ depicts the atmospheric decay of an emission pulse, as a fraction of the initially released quantity remaining in atmosphere at time s. Thus, $\varepsilon_i(s)$ is an impulse response function, describing the reaction of the pollutant stock to a one-off shock perturbation (a Green's function).[9] The formulation is general and can be applied to all pollutants, despite variation in the pollutants' decay profiles.

Unlike stock pollutants, which can be controlled through net emissions only, transient forcers can be adjusted more directly. Land cover is one example. Current land cover is determined by current land use (and land use history). Current land cover directly determines the surface albedo and its contribution to RF. Previous land cover[10] has no lasting effects that would contribute to today's RF. Thus the name: transient forcer.

2.2. Social Cost of Forcing

Climate change causes harm to ecosystems and human well-being (IPCC, 2014). Here, we use global mean temperature $T(t)$ as a proxy for climate change, and a temperature dependent damage function, $D(T)$, as a proxy for the aggregate social damage caused by climate change. The damages are measured in monetary terms ($\$\mathrm{yr}^{-1}$). In Supplement S1 we show how this monetary representation of damages emerges from a utility-based welfare maximization problem. The social welfare loss from temperature change is the net present value of future climate damages

$$L(t) := \int_0^{\infty} D(T(t+s))e^{-R(t,s)}ds, \tag{4}$$

where $e^{-R(t,s)}$ is a discount factor from time t to time $t+s$ and

$$R(t,s) := \int_0^{s} r(t+u)du. \tag{5}$$

Future damages are discounted using a time-dependent real interest rate $r(t)$. The welfare loss can be understood as a weighted average of future damages, in which the near-term damages have a higher weight than the distant ones. Welfare loss (4) is a reduced form presentation of a more complete description of economic welfare presented in Supplement S1. The loss of welfare is driven by rise in global mean temperature which in turn is caused by increased RF. *The Social Cost of Forcing*[11] *(SCF)* is a measure of the social harm (i.e. welfare loss) caused by an incremental unit of RF (i.e. a small and momentary increase in RF, see Supplement S2), i.e.

$$SCF(t) := \int_0^{\infty} \varphi(s)D'(T(t+s))e^{-R(t,s)}du, \tag{6}$$

where discounting is determined by Eq. (5). The social cost of forcing is the net present value of the marginal climate damage caused by the perturbation. The impulse response function, $\varphi(s)$, links the current forcing to future temperature change. The unit of SCF is $\$(\mathrm{Wm}^{-2}\,\mathrm{yr})^{-1}$, but since one Wm^{-2} change in RF causes notable changes in equilibrium temperature, SCF obtains very large values. Therefore, it is more convenient to use $\$(\mathrm{nWm}^{-2}\,\mathrm{yr})^{-1}$, i.e. one billionth of $\$(\mathrm{Wm}^{-2}\,\mathrm{yr})^{-1}$, as the unit price of RF.

The SCF emerges naturally in economic climate policy optimization models, as it is the Lagrange multiplier of the defining constraint for RF. If the optimization is based on non-monetary utility functions, the Lagrange multiplier needs to be transformed into monetary units by dividing it by current marginal consumption utility. This procedure is illustrated with a stylistic economic model in Supplement S1. In standard non-linear programming, the Lagrange multipliers are found as the marginal values of relevant constraint equations.

The SCF depicts the social costs of global forcers. If one is interested in local phenomena, such as pricing the warming impact of albedo of a local forest stand, it is useful to define a social cost measure for warming power, instead of RF. Such a measure is directly obtained from SCF by dividing it by Earth's surface area, A. The measure $A^{-1}SCF(t)$ has unit $\$(\mathrm{W\,yr})^{-1}$. It presents the social cost of warming the climate with annual average power of 1 watt, or equivalently, by producing one watt-year of heat. Since Earth's surface area is large (roughly $5.10 \cdot 10^{14}\,\mathrm{m}^2$), it is often practical to express prices of local warming power in $\$(\mathrm{MW\,yr})^{-1}$ (rather than $\$(\mathrm{W\,yr})^{-1}$).

2.3. Pricing Forcers

The SCC indicates the social cost of CO_2 emissions, i.e. the marginal social damage from emitting 1 tCO_2. Given our climate model (1–3) and welfare loss measure (4), we can derive similar social cost measures for all other forcers as well.

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[8] The impulse response is often divided into a product of a scalar climate sensitivity parameter $(\mathrm{K}(\mathrm{Wm}^{-2})^{-1})$ and a time profile (yr^{-1}) whose integral from zero to infinity is unity.

[9] Impulse response is unitless.

[10] Notably, current land cover may be affected by previous land use but not by previous land cover.

[11] Previously a similar concept has been utilized by Lutz and Howarth (2014) to derive a price for the warming impact of forest albedo using the DICE model (Nordhaus, 1992, Nordhaus, 2014). Here we present the concept in a more general context.

The social cost of a pulse forcer j is (see Supplement S2)

$$SC_{S_j}(t) := \int_0^\infty \varepsilon_j(s) \frac{\partial F_P(\mathbf{S}(t+s))}{\partial S_j(t+s)} SCF(t+s) e^{-R(t,s)} ds, \tag{7}$$

where $\varepsilon_j(s)$ indicates the fraction of emissions still airborne after s years and $\partial F_S / \partial S_j$ is the marginal change in RF due to the marginal change in a given pollutant stock. The RF caused at any future point in time is valued according to the SCF. The price of the forcer is obtained by integrating the present value of the damage over the infinite time horizon. If the pollutant in question is CO_2, (7) is the familiar SCC formula. However, a price for any other pulse forcers can be derived similarly. Eq. (7) highlights that the damage measure, SCF, is a common component in the social cost measures for all pulse forcers.

The social cost of a transient forcer[12] is

$$SC_{T_i}(t) := \frac{\partial F_T(\boldsymbol{X}(t))}{\partial X_i(t)} SCF(t). \tag{8}$$

As the effect of transient forcing is instant, its social cost does not include persisting effects from pulse decay. For the same reason, there is no need for time discounting. From the mathematical point of view, transient forcers are instantly decaying special cases of pulse forcers. Their decay profile $\varepsilon_j(s)$ can also be described as a delta function. Notably, hybrid forcers (which affect RF through both transient and pulse-like mechanisms) can also be priced by valuing both elements separately and then summing them up to a single price.

The social costs (7, 8) can be interpreted as the socially optimal prices for the forcers. They can also be used to measure the relative harmfulness of different forcers. Since the prices are based on rigorous cost-benefit analysis, the approach is theoretically consistent and enables comparisons between pulse forcers and transient forcers.

We define a relative measure of harmfulness which we call the Social Cost Ratio (SCR),

$$SCR_a := \frac{SC_a}{SC_{CO_2}}. \tag{9}$$

In Eq. (9), the SCC (calculated using Eq. (7)) is the standard against which other forcers' unit social costs (calculated using Eq. (7) or (8)) are compared to. This approach is in line with previous measures such as GWP and GTP which also compare the impacts of other forcers to CO_2. However, while GWP and GTP measure the relative contributions of distinct forcers from a physical standpoint, SCR measures their relative contributions to social damage. Reducing damage is the correct target for an effective climate policy. The SCR reduces to GWP if the present value of SCF, $e^{-R(t,s)}SCF(t+s)$, is time-invariant[13] and if the time horizon used in the calculation of SCR (which is usually infinite) is artificially truncated to the same length as the time horizon as in the calculation of GWP.[14] In general, the time-invariance assumption is not satisfied in economic models.

3. Materials and Methods for Numerical Examples

3.1. Outputs From the DICE2013R Model

DICE2013R is a global integrated assessment model (IAM) designed by William Nordhaus (see e.g. Nordhaus, 2014, Nordhaus and Sztorc, 2013). 'DICE' stands for Dynamic Integrated Climate-Economy model; '2013R' is the newest version in a line of models extending back to the early 1990′s (Nordhaus, 1992, 1993). In the model, the timing and intensity of emission abatement is optimized over time to maximize aggregate social welfare. The tradeoff between the damage caused by climate change and the welfare loss caused by abatement (i.e. abatement costs) is balanced in the optimization. The solution contains the optimal SCF and SCC trajectories which can be used to outline an optimal climate policy. The model is described in detail in Nordhaus and Sztorc (2013). Below, we discuss how it was modified for the purposes of this study and explain the model outputs that were derived.

In DICE, emission abatement controls the path of carbon emissions. As the model is optimized over time, the trajectory of atmospheric CO_2 is determined endogenously. However, the RF trajectory of other forcers, such as aerosols and non-CO_2 GHGs, is assumed to be exogenous. All RF that is not CO_2-induced is lumped into a single variable called 'exogenous forcing'. The variable's default time path roughly coincides with non-CO_2 RF in IPCC's RCP45.[15] For the purposes of this study, we substituted the default assumption[16] with a trajectory that exactly matches RCP45 as described in Meinshausen et al. (2011) with cyclicality in solar RF smoothed out. The use of a specific RCP enables distinguishing the mixing-ratios of exogenous GHGs (this information is required in Section 3.2). Changing the exogenous RF scenario has little impact on the SCC and SCF estimates derived using DICE (Supplement S3).

The modified DICE model was run for 200 periods (1000 years). Data from the first 700–900 years of the model run were used in our analysis depending on the time preference rate. After that timeframe the variable values become unreliable as numerical imprecision and end of model horizon effects start to distort the results. Three outputs were obtained: (1) a trajectory for atmospheric CO_2 concentration under optimal CO_2 abatement policy, (2) a trajectory for the real interest rate (used for discounting), and (3) a trajectory for SCF under optimal CO_2 abatement policy. The derivation of the SCF trajectory is much like the derivation of the SCC estimates, for which the model has been used for previously (see e.g. Nordhaus, 2014, US Government, 2015). In DICE, SCC is obtained as the shadow price of the marginal ton of CO_2 released in a given period. Likewise, SCF can be derived as the shadow price of the marginal unit of incremental RF in a given period (Lutz and Howarth, 2014). The principle is outlined in Supplement S1. As DICE has a five year time-step, the data for intervening years was interpolated linearly. The time-series were extended beyond the reliable DICE time horizon by statistical fitting (Supplement S4).

To illustrate the effect of discounting we derived the results under two distinct discounting schemes. In the first scheme, the pure rate of time preference is 1.5%. Hence, the real interest rate (that is used for discounting) starts at roughly 5.2% in 2010 and declines over time towards 1.5%, as the economy converges to a steady state over the next centuries. In the second scheme, the pure rate of time preference is 0.1% and the interest rate declines from roughly 4.4% to 0.1% over a similar time horizon. The first scheme is in line with the default settings of the DICE model which are based on a "descriptive approach" to discounting. Advocates of this approach hold that the pure rate of time preference should be inferred from decisions observed in the financial markets (see e.g. Nordhaus (2007) or Arrow et al. (2012) for discussion). An alternative to the descriptive approach is the "prescriptive approach". Advocates of this approach hold that the choice of pure rate of time preference should be based on ethical principles and argue that

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[12] Previously, the pricing of specific transient forcer, namely forest albedo, has been studied by Lutz and Howarth (2014). Here we present the concept in a more general context.

[13] A time-invariant present value of the SCF means that the SCF increases at the same rate at which future damages are discounted and, thus, the two effects cancel out. A special case of this is the one in which the SCF is constant and zero-discounting is applied. However, applying zero-discounting does not necessarily imply that the SCR is close to GWP (for the given time horizon), as the SCF may change over time.

[14] The relation between cost-based measures and GWP is further discussed in Tol et al. (2012).

[15] The IPCC probes alternative climate scenarios using Representative Concentration Pathways (RCPs). Each RCP consists of a set of time trajectories for RF caused by different climatic forcers. The RCPs are named after their peak in aggregate RF. Thus, in RCP45, RF peaks at roughly 4.5 $Wm^{-2}.Wm^{-2}$

[16] Notably, however, we do not extend the model to include the optimization of other climate forcers (which is a large modelling task that is well beyond the scope of this study). We simply substitute one exogenous RF scenario in the model, with an alternative scenario in which the GHG-specific time trajectories are explicit (instead of total RF only).

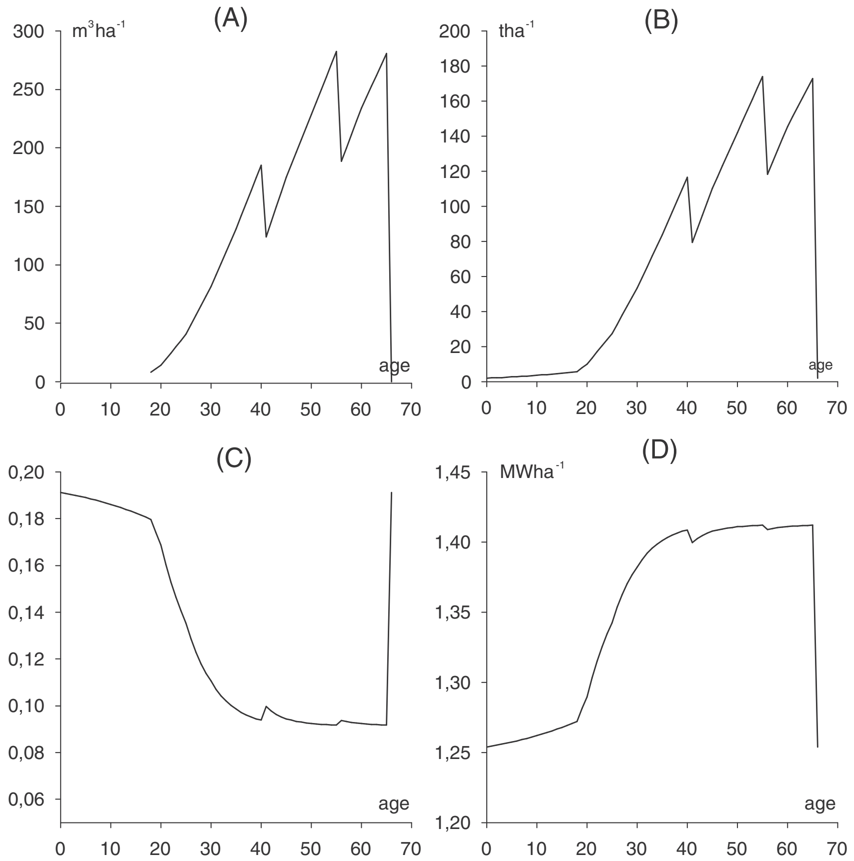

Fig. 1. Simulated development of (A) growing stock volume, (B) biomass, (C) midsummer albedo and (D) mean annual net shortwave flux, in a Norway spruce stand in Southern Finland over a 66 year rotation.

"it is ethically indefensible to discount the utility of future generations, except possibly to take account of the fact that these generations may not exist" (Arrow et al. (2012)). Our second discounting scheme is in line with this prescriptive approach. The 0.1% rate of pure time preference depicts the hazard rate of human extinction (per year), as assumed in Stern et al. (2006). For easy reference, we name the first scheme "higher discounting" and the second scheme "lower discounting".

3.2. Pricing and Comparing the Harmfulness of CO_2 and CH_4 Emissions

The Social Cost of Carbon (SCC) and the Social Cost of Methane (SCM) were calculated using a discrete-time analog Eq. (7), with a one year time-step. We approximated the infinite time horizon by a 10,000-year time span.[17] The real interest rate trajectory (calculated using DICE and extended as described in Supplement S4) was applied in discounting. Impulse response functions describing the atmospheric decay of CO_2 and CH_4 pulses were obtained[18] from Myhre et al. (2013). The marginal RF caused by the fraction of each pulse remaining in the atmosphere in a given year after emission depends on the atmospheric mixing ratios of well-mixed GHGs; the marginal RF of CO_2 depends on the atmospheric CO_2 concentration, whereas the marginal RF of CH_4 depends on the concentrations of CH_4 and N_2O (Myhre et al., 1998, IPCC, 1990).[19] In order to determine marginal RF in each year, the future atmospheric CO_2 concentration was projected using DICE (see previous section). Corresponding exogenous projections for the atmospheric CH_4 and N_2O were obtained from RCP45 (Meinshausen et al., 2011). The value of the damage caused by RF in each future time period, was calculated by pricing RF according to the current SCF, obtained from DICE (see previous section).

To illustrate the difference between SCR and GWP as means of measuring tradeoffs between GHGs, we calculated the SCR for methane (price ratio of CH_4 to CO_2) and used the same data to calculate GWP, as outlined in Lashof and Ahuja (1990).

3.3. Pricing the Warming Effect of Forest Albedo

To calculate the development of the social value of forest albedo-induced RF with stand age, we simulated the growth and treatment of a Norway spruce (*Picea abies*) stand over a single rotation in Hämeenlinna, Southern Finland[20] using MOTTI software (version 3.0). MOTTI is a stand-level forest simulator, which can be used to study the impacts of forest management on the development of stand-level forest attributes in Finnish growth conditions (Hynynen et al., 2002, Salminen et al., 2005). It has been statistically calibrated using historical data from Finland and works most reliably when the applied management coincides with the most common practices. Therefore, in our example stand management is assumed to follow (national, voluntary) good practice guidelines (Äijälä et al., 2014).

The development of the stand's growing stock volume (GSV) is shown in Fig. 1 (Panel A). The stand is thinned twice (at ages 40 and 55) and is clear-cut at age 65. Total aboveground biomass is shown in Panel B. Biomass (tha^{-1}) was estimated from GSV ($\text{m}^3\ \text{ha}^{-1}$) according

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[17] Although a fraction of a CO_2 pulse remains airborne indefinitely, the discounting of the damages, and the fact that in the distant future SCF approaches zero, reduce the approximation error (caused by the use of 10,000 years as a proxy for the infinite time horizon) to a negligible level.

[18] Original source of CO_2 impulse response function: Joos et al. 2013.

[19] In our calculations the radiative efficiency of methane was scaled to include the effects of ozone and stratospheric water, as in Myhre et al. (2013) (page 8SM-17).

[20] Assumptions: (1) The stand is located on Mineral soil. (2) The stand is established by planting 2000 seedlings (with a 100% survival rate),

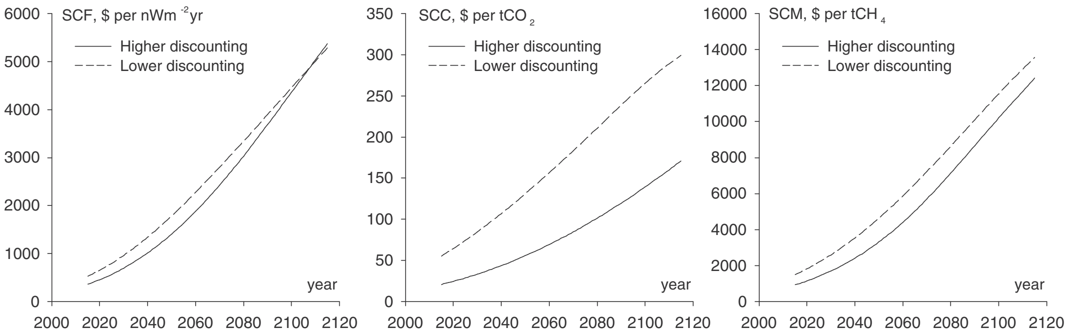

Fig. 2. Social Cost of Forcing (SCF), Social Cost of Carbon (SCC) and Social Cost of Methane (SCM) Trajectories for the Years 2015–2115.

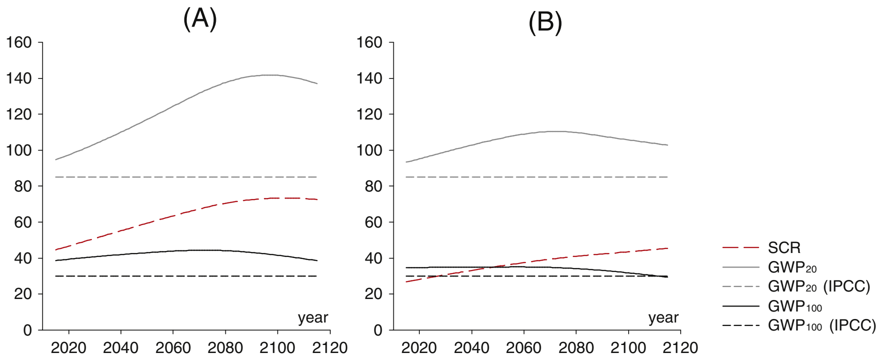

Fig. 3. The trade-off between Carbon dioxide and Methane as indicated by SCR and GWP assuming (A) higher discounting and (B) lower discounting. The same development of atmospheric mixing ratios was assumed in the calculation of GWP_{20} and GWP_{100}, as in the derivation of SCC and SCM (the GWP values in Panels A and B differ, due to the independent development of GHG mixing ratios in separate model runs). The GWP values recommended by the IPCC (Myhre et al., 2013) are shown for comparison.[25]

to the method outlined in Lehtonen et al. (2004). As GSV data were not available for the first 18 years, the development biomass in young stands was modelled assuming exponential growth, starting from 2 tha^{-1} at age 0 and reaching 5.8 tha^{-1} at age 18.

A relationship between stand biomass and summer albedo[21] was estimated using data obtained from Lukeš et al. (2013). A nonlinear regression was fit into the data (Supplement S6). The fit was used to estimate albedo based on total aboveground biomass in the stand (Fig.1, Panel C).

The top-of-the-atmosphere net shortwave (SW) flux (i.e. difference between the downwelling flux and the upwelling flux) is a measure of the energy transferred to Earth and its atmosphere from solar irradiance. Earth's surface albedo affects the net SW flux. Values for the mean annual net shortwave (SW) flux at the top of the atmosphere, for open shrub (1.254 MW ha^{-1}) and mature spruce forest (1.412 MW ha^{-1}), were obtained from Bright et al. (2011). Flux values between the two extremes (open shrub and closed canopy) were interpolated linearly based on change in summer albedo[22] (Fig. 1, Panel D).

Using the SCF, we can define the Social Cost of (local) albedo-induced warming (SCA), i.e. the value of the damage caused by the warming effect of local surface albedo ($\$ha^{-1}\,yr^{-1}$). Stand properties (here summarized by stand age, a, and calendar time t) determine the albedo of a forest stand. Surface albedo influences the local mean annual net shortwave flux at the top-of-the atmosphere,[23] $SW(a,t)$. This net flux is measured in Wha^{-1}. It can be directly priced according to its absolute warming power (for which the adequate price is $A^{-1}SCF(t)$, see end of Section 2.2). Hence, we define

$$SCA(a,t) := A^{-1}SCF(t)SW(a,t). \tag{10}$$

Notably, the social cost of local albedo-induced warming can be considered in absolute terms (as in (10)) or relative to a baseline by subtracting the opportunity cost, which is the value of the albedo-induced warming impact of an alternative land use (e.g. "the absolute SCA of closed-canopy forest" minus "the absolute SCA of open shrub).

4. Results

The SCF, SCC and SCM trajectories for the next hundred years are shown in Fig. 2. All three trajectories slope upwards. They indicate a climate policy that tightens over time. This feature is known as the climate policy ramp. It is characteristic to SCC estimates derived using DICE and other IAMs (e.g. Nordhaus, 1992). Notably, as the SCC and the SCM are both based on the SCF,[24] they both reflect the same tightening climate policy trend. The underlying upward-sloping SCF trajectory indicates increasing marginal damage of RF over time. In DICE, this increase is driven by the increase in global mean temperature (which increases the fraction of global GDP lost due to global warming) and economic

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[21] Formally: Directional Hemispherical Reflectance (DHR) in midsummer with SZA = 40°.

[22] Notably, forest albedo varies seasonally and hence the relationship the annual net SW flux and summer albedo may not be perfectly linear. However, defining a more refined model for the relationship is beyond the scope of this study.

[23] See Bright et al., 2011 for specifics.

[24] The SCF values used in the calculation of SCC and SCM are provided in Supplement S5.

[25] The shown IPCC values include climate-carbon feedbacks. These values are consistent with the approach applied in this study, as the impulse response function for carbon adopted from Joos et al. (2013) also includes climate-carbon feedbacks. The difference between the IPCC GWP and our own value is explained by the fact that IPCC GWP reference values are calculated assuming constant atmospheric mixing ratios (Myhre et al., 2013), whereas in our calculations the mixing ratios change over time. Previous studies have shown, that this causes a roughly 10% difference in the magnitude of the estimates (Myhre et al., 2013).

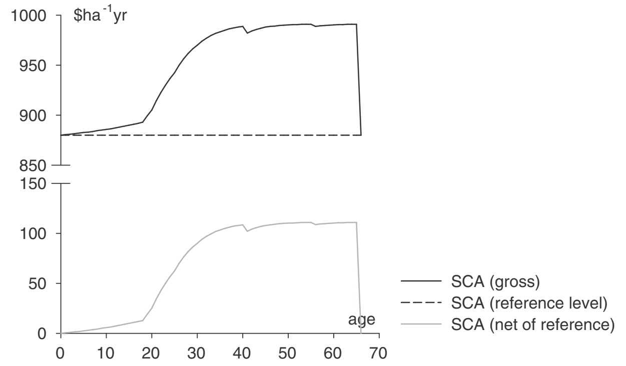

Fig. 4. The annual Social Cost of Albedo (SCA) of spruce forest (by stand age) compared to open shrub. The solid black line indicates the absolute social cost of the warming effect. The solid grey line indicates the cost relative to the reference level (i.e. open shrub). The SCA estimates are based on SCF in the year 2015 (higher discounting).

growth (which increases the global GDP and, thus, the absolute monetary value of the fraction lost due to climate damage).

Although SCC and SCM are both upward-sloping, they do not change in lockstep, because the impulse response functions for CO_2 and CH_4 differ. SCM increases faster than SCC and, therefore, their SCR also increases (Fig. 3). Notably, in our example (Fig. 3, Panel A), the SCR is always greater than GWP_{100} and always less than GWP_{20}. The discrepancy between GWP and SCR grows in the following decades. The difference between GWP and SCR illustrates the fact that the former is not automatically an adequate proxy for the latter. However, with suitable economic assumptions, the GWP (calculated for some arbitrary time horizon) and SCR (calculated for the infinite time horizon) may be temporarily (and coincidentally) close to each other, as in Panel B.

The SCA of one hectare of Norway spruce forest in Southern Finland is shown in Fig. 4. Over the rotation, the absolute annual social cost ranges from \$880 (open shrub) to \$990 (just before clear cut) with higher discounting.[26] Thus, the difference in the social cost of the warming impact of an open shrub and a mature forest is \$110 ha^{-1}. The thinning of the stand at ages 40 and 55 (Fig. 1) has relatively little impact on the social cost. Notably, in our example, the SCA is not taken into account in forest management optimization. However, the SCA concept allows its inclusion if/when albedo is included in the climate policy.

5. Discussion

5.1. Other Examples of Applying the SCF to Price Forcers

Above we have shown how all forcers, regardless of type, can be flexibly priced based on the SCF (Section 2) and provided two examples of how it can be done in practice. The pricing of pulse forcers is analogous to the derivation of the SCC which is a well-established and broadly understood concept. Hence, no further examples regarding their pricing are needed. However, the idea of pricing transient or hybrid forcers is not as broadly understood and attempts to price such forcers have been rarer. Below, we provide two further examples of how the SCF might be applied to these cases.

Anthropogenic Heat Flux (AHF) is a transient forcer (Washington, 1972, Flanner, 2009, Zhang and Caldeira, 2015). It is generated when e.g. fossil fuels are combusted for heat or other energy forms (generally, most of the generated non-heat energy, such as electricity, is also ultimately dissipated as heat). This heat –temporarily– warms the atmosphere. If the annual average power released as heat can be measured (in watts), it can be priced in a way that is very similar to the way in which albedo is priced in this study. In fact, the social cost of AHF is obtained directly as $A^{-1}SCF(t)$ (measured in $\$MW^{-1}\ yr^{-1}$) which, as explained in Section 2.2, depicts the annual cost of generating heat flux at annual average power of one megawatt.

Black carbon is a hybrid forcer (Ramanathan and Carmichael, 2008). It is first emitted into the atmosphere as an aerosol but becomes a transient forcer when it is deposited on snow (Hansen and Nazrenko, 2004, Flanner et al., 2007, Hadley and Kirchstetter, 2012). The warming impact[27] of black carbon in the atmosphere can be priced by treating it as a pulse forcer. The warming impact of black carbon on snow can be priced by valuing its surface albedo impacts. Notably, the price of black carbon emissions will vary according to geographic location, as atmospheric circulation affects the atmospheric lifespan of the pulses as well as the chance of deposition on snow and the duration of their effect on snow albedo.

5.2. Using and Improving the SCF

The SCF has two properties that make it useful in climate policy and economics. First, it can be flexibly used to value forcers regardless of their type. Second, it is a concise and effective way to communicate information.

This capacity to communicate information in a flexible format facilitates a natural division of labor between economists and end-users. Economists, who work with IAMs, can produce a single output that allows pricing forcers consistently. As the same output can be used to value any kind of forcer, economists can focus their efforts on refining SCF estimates rather than deriving and refining prices for multiple different forcers. Economists do not need to know what kind of forcers end-users are interested in pricing: end-users can price whatever forcers they wish. In practical applications, the role of the SCF is to complement rather than replace the SCC. As CO_2 is by far the most common forcer included in CBA, it is convenient to provide a price for carbon directly, rather than require it to be derived from SCF values every time a price is needed. The SCF offers a complementary means for pricing other, less common forcers for which prices are not readily available. Therefore, we recommend that SCC and SCF estimates (based on the same assumptions) should be published side-by side.

Another potential application for the concept, is for governments to publish 'official' SCF trajectories and (the associated) discount rates that can be used to harmonize climate policy across sectors. Given that climate policy is decreed democratically, it is not self-evident that such 'official' values will reflect the recommendations of professional economists or scientists. Rather, they are more likely to reflect a political compromise regarding the stringency of the policy. Nevertheless, such values can be used to harmonize climate policy in a way that is transparent and consistent across different climate forcers, given a politically decided level of stringency. For example, a regulator can use its stated SCF expectations to derive consistent taxes for carbon and methane, or to tax/subsidize land use based on albedo so that it is in line with the taxation of fossil emissions. A similar principle can also be applied in tradable emissions permit markets, where the CO_2 price is used as a benchmark for valuing other forcers. In the EU ETS, for example, the prices of PFCs and N_2O are currently obtained by multiplying the CO_2 price by the GWP value of the respective forcer (European Commission, 2012). The pricing consistency can be improved by replacing GWP by an SCR value that is based on the official SCF trajectory.[28]

Furthermore, official SCF values could be used in CBAs conducted for public projects, much like the official SCC values that are already published by the US government (US Government, 2015, Johnson and Hope, 2012). Providing similar SCF values would enable the inclusion

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[26] The results for SCA derived using lower discounting are not shown, as changing the price of warming power simply scales the results.

[27] Unlike most aerosols, black carbon has a warming impact in the atmosphere.

[28] Alternatively it might be interesting to consider whether it would be possible to restructure the permit market so that temporary RF quotas were auctioned instead of CO_2 quotas. In this case, it might become possible to price all forcers based on the benchmark price (which would be some variant of the SCF). However, as long as the CO_2 price is used as a benchmark, SCRs are needed as "exchange rates" between forcers prices.

of non-carbon climate impacts in the analyses –if there is the political will to do so. In some cases, the social value of these impacts may be high, as our albedo example demonstrates.

Deriving SCF estimates is technically feasible. The same IAMs that are used to estimate the SCC can also be used to estimate the SCF. We demonstrate this by producing the SCF trajectories applied in our numerical examples using DICE. Nevertheless, it should be noted that the trajectories utilized in this study are based on single, deterministic model runs. For comparison, the SCC estimates published by the Interagency Working Group on Social Cost of Carbon are based on 10,000 probabilistic model runs each (US Government, 2010, US Government, 2015). The same rigor should be applied to making proper SCF estimates for further use. Thus, the numerical examples provided in this study should be considered mere examples of how the forcers' prices can be calculated from a given SCF trajectory, rather than best estimates for the price of carbon, methane or albedo. In the future improved SCF estimates can be produced as a side-product of SCC estimates, as the same models and estimation procedure are required for both. Naturally, due to these methodological similarities, SCF estimates are also susceptible to the same uncertainties as SCC estimates (e.g. regarding damages see Tol (2012)).

The current SCC estimates published by the US Government extend to the year 2050 (US Government, 2015). To be useful, the SCF trajectories published by economists or governments should span much further into the future to enable the pricing of long-lived pollutants (7). In Supplement S5 we provide an example of what such data might look like. Many economists may be wary of publishing estimates spanning centuries into the future, knowing that no model can reliably project the development of the global economy that far and that large uncertainties are associated with damage estimates. However, two things should be kept in mind. First, the value of distant future damage is already included in the presently used SCC estimates (7), as CO_2 is a long-lived pollutant that contributes to RF over a long period. Publishing the SCF trajectory used to value this RF simply means explicitly stating the underlying assumptions regarding the valuation of future damages. In other words, it does not affect the reliability of the SCC estimates but improves their transparency. Similarly, valuing any other future climate impacts based on the SCF is as reliable as valuing the future impacts of a CO_2 pulse emitted today. Second, future damages are discounted in cost-benefit analysis, and the present value of distant future damage is usually relatively small[29] compared to that of more immediate effects. Thus, although the damage is uncertain, it has only little impact on today's prices for long-lived pollutants, and virtually no impact on those of short-lived pollutants and transient forcers. Moreover, despite the uncertainty, it is necessary to value future damages somehow if we wish to derive prices for long-lived pollutants. SCF values from IAMs are our best guess. Their reliability is tied to the general reliability of the IAMs.

5.3. Notes on the Link Between SCR and GWP

Traditionally, the climatic impacts of forcers have been compared using purely physical metrics, such as the GWP, which measure cumulative radiative forcing rather than the relative harmfulness of the impacts. Augmenting GWP with SCF and discounting creates the SCR which is its economic analogue in the sense that it can be used to measure the relative harmfulness of different forcers compared to CO_2. Previously, Tol et al. (2012) have shown that the GWP of forcer is a special case of its SCR, in which the damages are linear, there is no discounting and the time horizon is arbitrarily truncated to the same length as the time horizon of the GWP factor.[30] Our analysis shows that a combination of linear damages and zero-discounting is not necessarily required, as long as the present value of SCF remains constant and the time-horizon is truncated. However, as our numerical results illustrate, these conditions cannot be assumed to automatically hold in practice. Therefore, GWP is not an adequate metric for deriving consistent relative prices for other forcers based on the price of carbon.

5.4. Notes on Pricing Albedo's Warming Impact

Recently, the joint-optimization of forest rotations for timber production, carbon storage and albedo regulation has been considered by e.g. Thompson et al. (2009), Sjølie et al. (2013), Lutz and Howarth (2014), Lutz et al. (2016) and Matthies and Valsta (2016). A central question in this literature is how albedo should be priced. Several approaches have been proposed: e.g. converting the warming impact of albedo into CO_2 equivalents based on GWP or GTP metrics (Cherubini et al., 2012, 2013) and using the DICE model to derive a shadow price for albedo (Lutz and Howarth, 2014) –as is also done in this study. Lutz and Howarth (2015) compare these approaches, and show that conclusions regarding optimal stand management strongly depend on which approach is adopted. Establishing the optimal rotation therefore requires determining the correct way to price albedo. However, Lutz and Howarth (2015) do not assert that any particular pricing approach is more desirable than any other. In the light of this study, we conclude that in terms of pricing consistency, the approach proposed by Lutz and Howarth (2014) is better-suited for use in intertemporal cost-benefit analysis (such as the question of optimizing a the management of a forest stand) than the alternative GWP-based or GTP-based approaches.

In our numerical example, we measure surface albedo's warming impact based on the mean annual net SW flux at the top of the atmosphere, as proposed by Bright et al. (2011). The same method is applied in e.g. Lutz and Howarth (2014) and Lutz et al. (2016). Given that we measure albedo-induced warming correctly, our results suggest that the annual social cost of mature spruce stands' albedo effect is large in Southern Finland. This observation is in line with Betts' (2000) concern that, in some parts of the boreal zone, the warming impact of surface albedo changes may offset the benefits of increased carbon storage in forests. Reoptimizing forest management, accounting for the value of carbon storage and albedo, might therefore radically change the treatment of forests. So far, only Sjølie et al. (2013) and Matthies and Valsta (2016) have tackled this question in Nordic conditions. Such analyses can be further refined by pricing albedo according to the SCF rather than converting it into carbon equivalents using climate metrics. This calls for further study.

6. Conclusions

We have shown that the method, originally proposed by Lutz and Howarth (2014) for pricing forest albedo, can be generalized to price forcers of any kind. Lutz and Howarth (2015) call their approach the DICE method, after the DICE model (Nordhaus, 1992, 2014) which they utilize in their calculations. However, as we show in this study, the method generalizes to other IAMs as well. We therefore suggest that the shadow price of marginal radiative forcing should be called the Social Cost of Forcing (SCF), as the concept is independent of any specific IAM.

The SCF concept enables the consistent pricing of distinct forcers according to the social cost of their warming impacts. It has two properties that make it especially useful in climate policy and economics. First, it can be flexibly used to value forcers regardless of their type. Second, it is a concise, effective and transparent way to communicate information between economists, working with IAMs, and end-users wanting to incorporate the social value of the climatic impacts of various forcers into CBA or climate policy.

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[29] As long as the rate of increase in the SCF is sufficiently smaller than the rate of discount.

[30] Naturally, to match with the GWP, the SCR needs to be calculated for the same time horizon as the GWP.

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Appendix A. Supplementary Material

Supplementary material to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2016.11.014.

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