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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

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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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the two 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.

[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.