Climate Impacts on Natural Capital: Consequences for the Social Cost of Carbon

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Abstract

The effects of climate change on natural systems will be substantial, wide-spread, and likely irreversible. Warmer temperatures and changing precipitation patterns have already contributed to forest dieback and pushed some species towards extinction. Natural systems contribute to human welfare both as an input to the production of consumption goods and through the provision of non-use values (i.e. existence and bequest values). But because they are often unpriced, it can be difficult to constrain these benefits. Understanding how climate change effects on the natural capital stock affect human well-being, and therefore the social cost of carbon (SCC), requires understanding not just the biophysical effects of climate change, but also the particular role they play in supporting human welfare. This article reviews a range of topics from natural capital accounting through climate change economics important for quantifying the ecological costs of climate change, and the integration of these costs into SCC calculations.

Main Text

Anthropogenic climate change will alter patterns of temperature, precipitation, and weather extremes around the world throughout the 21st century and beyond. Even with ambitious mitigation policies in place, rates of warming will exceed anything in the historical record and likely anything in the last tens or even hundreds of thousands of years of Earth history (Tierney et al. 2020). Although rapid progress has been made in recent years in understanding the sensitivity of socio-economic outcomes to weather fluctuations and climate change (Carleton & Hsiang 2016; Dell et al. 2014; Piontek et al. 2021), some of the most direct, pervasive and irreversible effects of climate change will occur on ecological systems. Climate change will alter the productivity of natural systems, shift patterns of terrestrial vegetation, and push a potentially large number of species to extinction (Scholes et al. 2014; Urban 2015). Changes in the flows of valuable goods and services derived from these systems have implications for human welfare, but is only imperfectly captured in current estimates of the aggregate costs of greenhouse gas emissions, such as the social cost of carbon (SCC).

This paper will both review work on natural capital's role in the economy and human welfare and walk through how incorporating this theory into standard models of the coupled climate-economic system might alter estimates of climate change costs, with implications for policy-relevant quantities like the SCC. The focus of this paper is on the welfare effects of the ecological impacts of climate change impacts, excluding a more general discussion of the many interactions between climate change and natural systems. For instance, deforestation results in threats to biodiversity, loss of ecosystem services, and also contributes to climate change through release of CO_2 to the atmosphere. In addition, natural systems face anthropogenic threats other than climate change such as habitat destruction or local air and water pollution, which in many cases will be the most important determinants of ecosystem quality over the 21st century. Climate change will interact with these other environmental threats in complex ways, but those interaction effects are not discussed here. We also focus in this paper on ecosystem services other than agricultural production. Although agriculture is both heavily exposed to climate change impacts and dependent on natural capital inputs such as soil fertility, there is a large literature dedicated to the effects of climate change on agriculture, review of which is necessarily outside the scope of this paper (for recent reviews of this topic see Antle & Stöckle 2017; Blanc & Schlenker 2017; Carter et al. 2018).

We begin with a brief review of the concept of the SCC, how it is calculated and how ecological impacts are (or are not) integrated into models currently used to estimate it. We then provide background on the definition and measurement of natural capital, describe the expected biophysical effects of climate change, before reviewing how these effects can be integrated into standard climate-economy models.

1. The Social Cost of Carbon and the Representation of Ecological Damages

The SCC in year t is defined as the net present value of the impacts of one ton of carbon dioxide emitted to the atmosphere in that year. The SCC is specific to the baseline emissions path – in economic research it is often calculated along an optimal emissions pathway, where the global carbon tax is set equal to the SCC (Nordhaus 1992). In policy applications however, the SCC is typically calculated along a non-optimal no policy emissions trajectory (Rose et al. 2017). Calculating the SCC requires connecting greenhouse gas emissions to human welfare, which requires modeling the carbon cycle (emissions to atmospheric CO_2 concentration), the climate system (CO_2 concentration to global temperature) and the damages from climate change (temperature to human welfare). These calculations are done using cost-benefit integrated assessment models (IAMs), of which the three most widely used today are the DICE , PAGE, and FUND models (Anthoff & Tol 2014; Hope 2011; Nordhaus 2017).

Climate damages included in the SCC are, in principle, fully comprehensive. Even though everything is denominated in dollars, damages should include non-market impacts such as mortality and morbidity, effects on natural systems and loss of cultural heritage. Exactly how climate change impacts on natural capital are incorporated into these models is not always obvious. They are explicitly modeled only in FUND, which includes both damages associated with wetland loss to sea-level rise based on a meta-analysis of ecosystem services provided by wetlands in Brander et al. (2006) and a damage function capturing the non-use values of biodiversity decline with values based on Pearce (1993). Calibrations of these functions result in empirically small effects, contributing vanishingly small amounts to FUND's SCC (Diaz & Moore 2017; Rose et al. 2017).

Ecological impacts in PAGE are in theory captured in the "non-market" damage function, along with mortality damages, although the exact empirical basis for calibration of this damage function, and therefore the degree to which it does or does not include natural capital costs, is difficult to determine. DICE aggregates all impacts into a single damage function based on a weighted meta-analysis of studies reporting global welfare changes at different levels of warming (Nordhaus & Moffat 2017). However, as pointed out by Howard and Sterner (2017), a substantial fraction of these studies are based on regressions of GDP on temperature or temperature change, and are therefore missing non-market and non-use impacts derived from ecosystems. Sector-based studies using computable general equilibrium models capture some sectors dependent on natural capital such as agriculture and forestry (Johnson et al. 2021), but it is fair to say that ecological climate damages are not explicitly, and in most cases not implicitly, represented in the studies supporting the DICE damage function.

One important exception to note is the case of carbon sequestration. Often included as an important component of the ecosystem services provided by landscapes, carbon sequestration plays a particular role in SCC calculations. Because any SCC calculation requires translating carbon dioxide emissions into temperature change, it requires some implicit (via parameterization) or explicit representation of uptake of carbon from the atmosphere by the biosphere (i.e. carbon sequestration), usually as part of a simple carbon-cycle model within the IAM. Currently the biosphere takes up about 30% of anthropogenic emissions to the atmosphere (Friedlingstein et al. 2020), but it is likely this sink will weaken with future climate change and warming and drought disrupt terrestrial vegetation growth (Anderegg et al. 2020; Hubau et al. 2020). Dietz et al. (2021) point out that carbon cycle models within the IAMs used to calculate the SCC are missing this weakening biospheric sink as well as a similar feedback that reduces the size of the ocean sink as a function of warming. They estimate omission of these carbon cycle feedbacks leads to an underestimate of the SCC by about 10% in 2020, growing to over 20% by 2100. Because carbon sequestration is explicitly represented within IAMs as part of the SCC calculations, discussion in the rest of the paper should be understood as effects on ecosystem services other than carbon storage.

2. *Natural Capital and Ecosystem Services*

This section presents a review of the concept, definition and measurement of natural capital and ecosystem services, before discussing how these can be incorporated into IAMs and therefore better represented in SCC calculations.

Broadly speaking, the motivation for natural capital accounting and ecosystem service valuation arises from the observation that natural systems provide a range of benefits to humans. Because many ecological goods are common-pool resources or public goods, many are characterized by imperfect property rights and therefore their full value will not be reflected in market transactions or national accounting data such as GDP. The set of benefits derived from natural systems can be divided into use and non-use goods (Turner et al. 2003). Use values of nature arise when natural systems interact directly with the society or manufactured capital, such as the flood-protection benefit mangroves provide to coastal cities or the raw materials used in producing market goods. Non-use values arise without interacting with nature, which could be either for the sake of nature itself (existence value) or the sake of future generations (bequest value; Krutilla 1967).

Natural capital is part of society's productive base, producing flows of ecosystem services. The analogy is to more typical forms of capital assets, which are stocks of wealth that can be used to produce a flow of benefits into the future. Following Dasgupta (2014), the total natural capital stock at time t can be written as the sum over individual natural assets (soils, forests, wetlands etc) multiplied by their shadow price:

$$N(t) = \sum_i p_i(t) n_i(t) \quad \text{Equation 1}$$

The shadow price, $p_i(t)$ gives the present value of the stream of benefits derived from an additional unit of the natural asset, conditional on the socioeconomic policies in place and the natural capital growth deriving from ecological dynamics and human impact.

Fenichel and Abbott (2014), building on capital pricing theory further develop the determinants of the asset price $p_i(t)$. They derive an expression that describes this price as a function of the marginal change in the flow of ecosystem services with an increase in the natural capital stock (which in turn will depend on the specifics of institutions managing access to the ecosystem goods), modified by a capital gains term associated with changing scarcity value, divided by the discount rate adjusted for the changing growth dynamics from marginally higher stocks.

Applications of this approach have included valuing fisheries stocks, including under non-optimal management (Fenichel & Abbott 2014), and the agricultural value of the Kansas High Plains Aquifer (Fenichel et al. 2016a). For ecosystem goods other than crops, fish, or timber (where market prices are readily observable), measuring the marginal dividends (change in the flow of benefits with a marginal change in the capital stock) can be particularly challenging since it requires the application of non-market valuation approaches. Accounting for non-use values such as existence and bequest values adds further complexity since these can be measured only using stated-preference approaches. Some papers have argued that these values can be bounded from below using observations of the costs societies are willing to undertake to preserve species existence, though these tend to be two orders of magnitude lower than stated preference estimates (Maher et al. 2020; Moore et al.).

2.1 Measuring Global Natural Capital Stocks and Sustainability

A challenge with integrating natural capital accounting into SCC estimates is that, because climate change is a global externality, anything less than full global coverage is insufficient for SCC calculations. Both the World Bank and the UN Environment Program (UNEP; World Bank 2006; Lange et al. 2011; Managi & Kumar 2018), have been developing approaches to incorporate natural capital accounting into national accounts data. The World Bank Wealth of Nations report (Lange et al. 2018) includes energy and mineral deposits, cropland, timber and non-timber services from forests and protected areas. Valuation of energy, minerals, timber and agricultural land uses market prices, non-timber forest benefits are based on a meta-analysis of forest ecosystem services by Siikamaki et al. (2015). Protected areas are valued only using the option value of pasture or cropland that might be grown on the land, making it a lower bound estimate missing any recreational or non-use values derived from those areas.

The UNEP Inclusive Wealth Report undertakes a similar exercise, though also includes valuation of fisheries stocks and a broader array of non-timber forest benefits based on the Ecosystem Service Valuation Database by Van der Ploeg & De Groot (2010).

Including measures of natural capital assets in national accounts is critical for operationalizing the concept of sustainability, which is typically defined as ensuring non-declining intergenerational well-being (Arrow et al. 2012). Because well-being derives from a (broadly defined) set of assets, this sustainability criterion is equivalent to ensuring that the value of these assets is not declining over time (Dasgupta 2021; Dasgupta & Mäler 2000; Hamilton & Clemens 1999). In other words, a fully comprehensive or inclusive measure of wealth including natural capital, human, institutional and social capital, as well as more traditional manufactured capital should be steady or increasing (Dasgupta 2001; Hamilton & Hartwick 2014). This definition of sustainability allows for substitution between natural and other forms of capital, and for that reason is sometimes called "weak sustainability" (Pearce & Atkinson 1993). However, even using this weak form of sustainability, UNEP's 2018 Inclusive Wealth Report found only 84 out of 140 countries met this criteria (Managi & Kumar 2018).

3. Ecological Impacts of Climate Change

Anthropogenic emissions of greenhouse gases affect natural systems through a number of pathways, including CO_2 fertilization, ocean acidification, sea-level rise, in addition to changes in temperature and rainfall patterns. Table 1 maps some of the most important pathways by which these climate drivers map, via ecological changes, into changes in ecosystem service provisions, with implications for human welfare.

Higher CO_2 concentrations in the atmosphere are partially taken up both through the biosphere via higher primary productivity (i.e. the CO_2 fertilization effect which has taken up approximately 30% of anthropogenic emissions in the 2010-2019 decade (Friedlingstein et al. 2020)), and abiotically via dissolution in the ocean as carbonic acid (22% of 2010-2019 emissions, (Friedlingstein et al. 2020)), contributing to ocean acidification. The remaining airborne fraction of anthropogenic CO_2 emissions disrupts the radiative balance of the planet and contribute to climate change, the most immediate and most widespread consequence of which is higher temperatures.

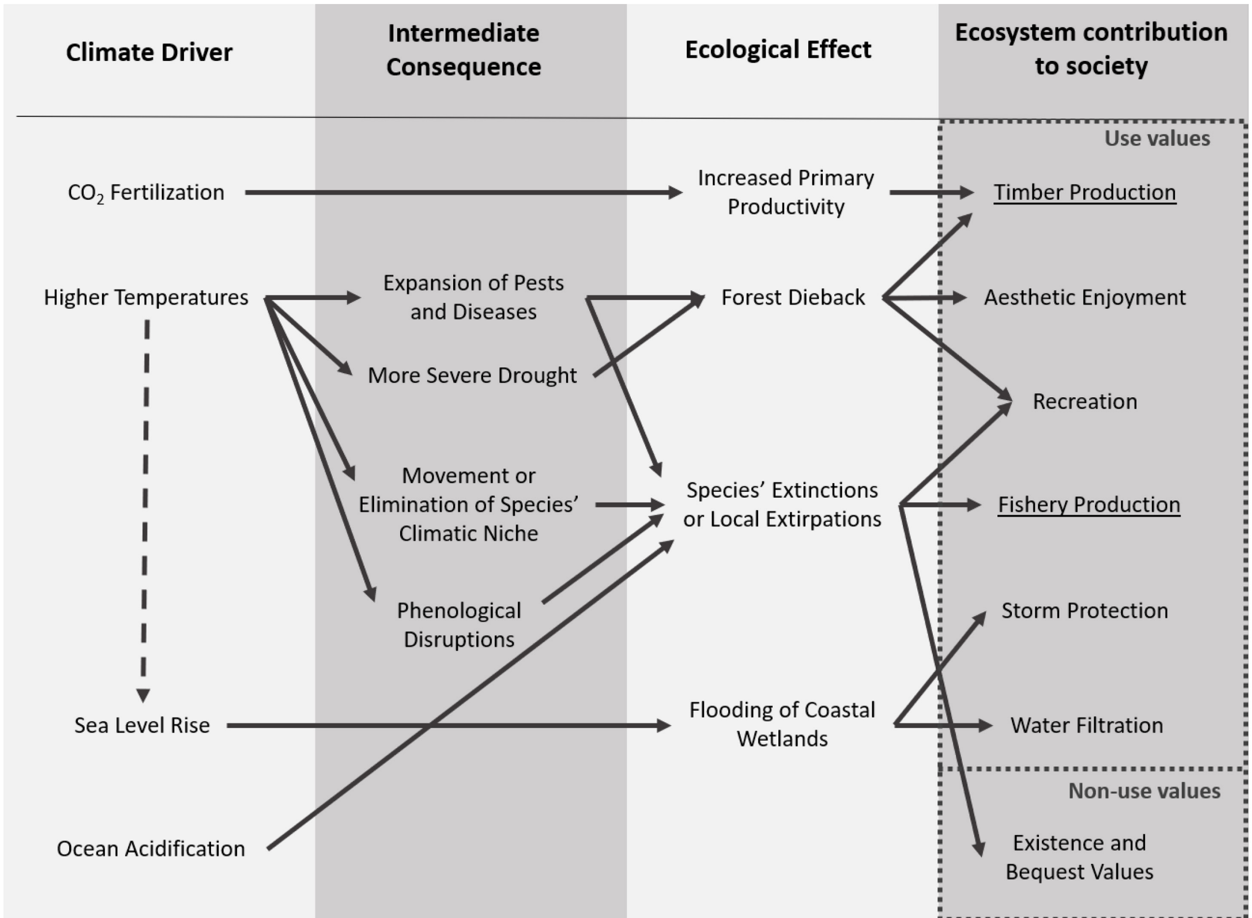

Table 1: Diagram relating some of the most well-understood, direct, and widespread physical effects of greenhouse gas emissions (Climate Drivers) to their ecological effects on natural or lightly-managed systems, and effects on human welfare via ecosystem service provision. This is not an exhaustive catalog of the effects of climate change on natural systems and there may be additional important impacts in particular locations. Ecosystem services are categorized into use and non-use values. Underlining indicates market goods.

Higher temperatures, particularly rates of warming projected for the 21st century (likely unprecedented in the tens of millions of years of Earth history (Tierney et al. 2020)) can disrupt ecological systems in a number of ways. In arid areas, higher temperatures will increase the severity of droughts, even absent any changes in rainfall: agricultural and ecological measures of drought severity are based on the balance between the supply of water to a region (via precipitation) and the atmosphere's "demand" for that water via evapotranspiration (Dai 2013; Touma et al. 2015). Since evapotranspiration increases rapidly at higher temperatures, hotter droughts dry out soil moisture more rapidly and can have more severe agro-ecological effects than cooler droughts (AghaKouchak et al. 2020; Diffenbaugh et al. 2015; Zscheischler et al. 2020).

Large-scale diebacks of forests around the world have been linked to climate change, both via drought and the spread of pests and diseases better able to survive winters in the warmer climate (Seidl et al. 2017). A concern is that wide-spread tree mortality will partly offset, or even eliminate, the biospheric carbon sink leading to more rapid CO_2 accumulation in the atmosphere and even faster climate change (Anderegg et al. 2020; Hubau et al. 2020). Changes in temperature, rainfall, and CO_2 concentrations will redistribute terrestrial vegetation around the world. Most models project reductions in vegetative carbon over the Amazon and increases in boreal ecosystems (Sitch et al. 2008).

Climate is a key predictor of species' distributions: Ecologists describe species as having a particular climate niche – a range of preferred temperature and rainfall in which the species is observed (Wiens et al. 2009). Rising temperatures will change the locations of that climate niche, in most cases pushing it towards higher latitudes or up in altitude. If a species' climate niche ceases to exist, or if the rate of dispersal (movement across space) is unable to track the speed of climate change, then the species may be at risk of extinction. Many studies in ecology have used species range maps combined with climate model projections to estimate the fraction of species threatened with extinction by climate change. For example, Urban (2015) reviewed 131 such studies, finding that on average these studies project-5.2% of species to be at risk of extinction under 2 degrees of warming and 8.5% under 3 degrees.

These estimates based mostly on climate niche modeling are likely to underestimate, perhaps substantially, the full effect of climate change on extinction risk, since they largely do not account for interactions between species. For instance, warmer temperatures can change the seasonal timing (phenology) of plant reproduction, often particularly a problem for migratory species relying on particular plants or habitats and particular times (Robinson et al. 2009). Coral reefs are threatened both by ocean acidification and by warmer temperatures driving increasingly-frequent marine heatwaves (Hughes 2003) and provide habitat for large fractions of marine species, many of which will be affected if coral reefs disappear (Jones et al. 2004). Expanding ranges of pests and diseases can threaten refugia of endangered species, as recently documented for white-bark pine in the Sierra Nevada (Dudney et al. 2021).

4. *Incorporating Natural Capital into the SCC*

Black boxes and arrows in Figure 1 give a schematic representation of the canonical DICE IAM developed by William Nordhaus (1992, 2017). In this representative agent model, labor (or human capital) and capital produce economic output using a Cobb Douglas production function. Production is split between savings, which is invested in the depreciating capital stock, and consumption, which contributes to utility. Production is also associated with greenhouse gas emissions that increase the stock of CO_2 in the atmosphere, which in turn increases global temperature. This has a negative effect on production via the damage function. CO_2 emissions from production can be reduced, at some cost, via mitigation (not shown). The savings and mitigation rates each time period are optimized to maximize discounted utility.

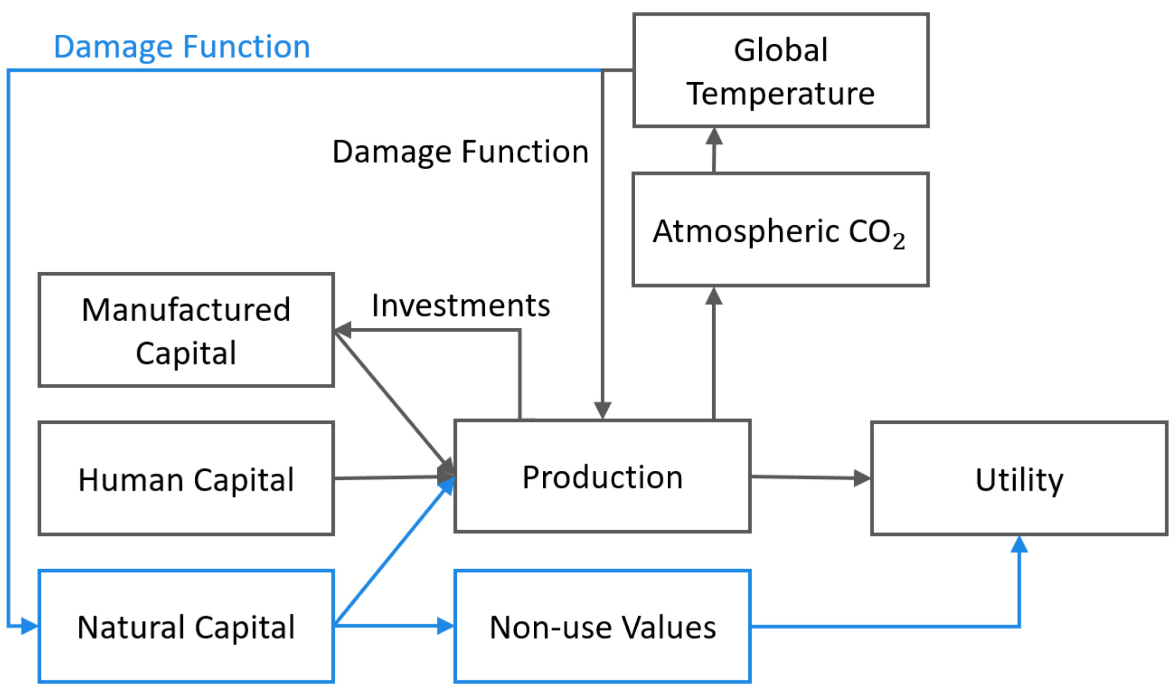

Figure 1: Schematic diagram of the canonical DICE model (shown in black) with expansions proposed in Bastien-Olvera and Moore (Bastien-Olvera & Moore 2021) to explicitly model the role natural capital plays in contributing to human welfare and the impacts of climate change on ecological systems.

Blue boxes and arrows show an expansion of the DICE framework, following Bastien-Olvera and Moore (2021), to explicitly model the role of natural capital in production and utility as well as the ecological impacts of climate change represented as a second damage function. This expanded framework explicitly represents the role of natural capital in producing both use values, as an input to production, and non-use values, as a direct input into the utility function. Subsequent sections of this review walk through the three primary modifications of DICE in this framework – the production function, the utility function, and the damage function – and discuss how explicitly representing natural capital damages might affect estimates of climate change costs.

4.1 *Production Function*

Economic output in DICE is given by the classic Solow-Swann growth model (Solow 1956) in which exogenously growing total factor productivity, exogenously growing population, and an endogenous capital stock determine production and growth[1]. Labor and capital (generally understood to mean manufactured capital) are the two factors of production, moving away from earlier work that had considered land as a third factor (Gaffney 2008). In his original work, Solow explicitly states that "there is no scarce nonaugmentable resource like land" (Solow 1956), effectively assuming that land, resources, or natural systems more generally impose no fundamental constraint on production.

The question of whether natural resources belonged in the production function as a third factor of production was an active area of research and debate in the 1970s, partly prompted by work such as the *Limits to Growth* (Meadows et al. 1972) which predicted economic collapse upon exhaustion of resources. Criticism of this work by economists emphasized the importance of establishing the substitutability between natural resources and other inputs in production (e.g. Stiglitz 1974). If these natural resources (N) are perfectly substitutable with capital and labor (i.e. $Y = A(\alpha_1 K + \alpha_2 L + \alpha_3 N)$, where A is total factor productivity) then they impose no fundamental limit on production and "the world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe" (Solow 1974). If instead resources are only partially substitutable with other inputs, for instance in a three-factor Cobb-Douglas production function (i.e. $Y = A(K^{\alpha_1} L^{\alpha_2} N^{\alpha_3})$; a special case of a constant elasticity of substitution production function[2]), then production can be maintained for any non-zero value of N, but requires increasing inputs of labor and capital as N declines.

[1] Note that the other major IAMs calculating the SCC – FUND and PAGE – do not include a growth model. Instead population and per-capita GDP growth are specified exogenously.

[2] The Cobb-Douglas production function imposes a constant elasticity of substitution equal to one. However, the closer to zero the elasticity of substitution gets, the less the substitutability between the factors of production. The choice of this parameter and the assumption that it is constant have been widely used in economics due to its mathematical tractability, but this is a particular modeling choice that could be more widely investigated.

Bastien-Olvera and Moore (Bastien-Olvera & Moore 2021) substitute DICE's two-factor production function for a three-factor Cobb-Douglas production function with constant returns to scale:

$$Y = A(K^{\alpha_1}L^{\alpha_2}N^{\alpha_3}); \qquad where \quad a_1 + a_2 + a_3 = 1 \qquad \text{Equation 2}$$

Assuming the natural capital stock N is fixed, then this change alone slows baseline economic growth rates, even with an optimized savings rate, since a growing population and capital stock translate into smaller increases in production. If the stock of natural capital is declining, for instance due to the impacts of climate change, then those impacts will affect the growth rate and have a long-lived effect on the level of output, similar to other persistent climate change damages such as effects on the depreciation rate or on TFP growth (Kikstra et al. 2021; Moore & Diaz 2015).

In reality, the natural capital stock N is unlikely to remain fixed even in the absence of climate change. Renewable resources such as fisheries or forests exhibit biophysical growth dynamics related to the carrying capacity of the system and the natural rate of increase (Anderson & Seijo 2010). Externalities of human activity other than climate change might also affect the dynamics of the stock (Hackett & Moxnes 2015; Liang et al. 2021). Finally, society might also divert part of production into investments to restore, replenish, or expand the natural capital stock, just as production is invested in manufactured capital in the standard DICE model. Bastien-Olvera and Moore (2021) model this possibility and find relaxing the constraint on the size of the natural capital stock by allowing investment of output in a natural capital asset leads to large investments and much larger stocks. However, it is still unclear how effective these hypothetical investments could be in growing the natural capital stock.

The DICE model has just one global region, but reliance on natural capital for economic production is not uniform around the world. In particular, global accounting of natural capital by the World Bank and UNEP (discussed in Section 2.1) documents a particular reliance on natural capital in poorer economies: as countries get richer, their stocks of manufactured and human capital grow and the relative importance of natural capital in national assets declines (Figure 2).

Variation across countries in the importance of domestic natural capital in production implies there will be heterogeneity in the welfare effects of climate change's ecological impacts, even if the biophysical effects were identical across countries. Because economic production in low and lower-middle income countries relies heavily on provisioning and regulating ecosystem services such as pollination, forests, and fisheries (Johnson et al. 2021), these effects are likely to be regressive: the same fractional reduction in the natural capital stock will lead to larger output declines in poorer countries than in richer countries. In reality, there are reasons to believe biophysical effects of climate change might also be worse in poor countries, which also tend to also be warmer. For instance, while high northern latitudes might see expansion of forests, forest dieback is projected in at least some tropical regions (Sitch et al. 2008). Similarly, cooler richer countries might see migration of fish stocks into territorial waters whereas poorer, warmer countries might see net outflows (Cheung et al. 2009). The distributional effects of climate impacts become more pronounced when considering impacts in non-priced goods that make up the largest welfare source in societies with subsistence economies (Hertel & Rosch 2010). This pattern also appears to hold for within-country income groups. For instance, Hsiang et al. (2017) show that county-level climate damages in the United States increase by approximately one percent for each reduction in income decile.

These distributional effects are lost if using only a single-region global model and require the use of more highly-resolved, multi-region models. Regressive climate change impacts can substantially increase the SCC if using equity-weighting, which takes into account different marginal utility of consumption, to aggregate across regions (Anthoff & Emmerling 2019; Dennig et al. 2015).

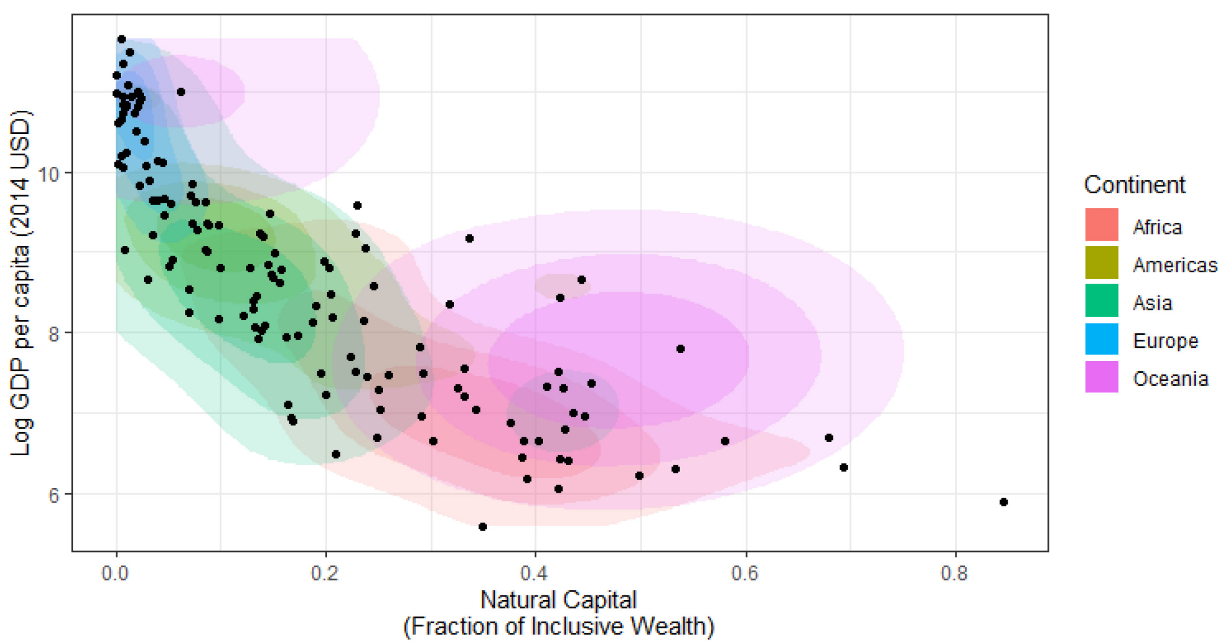

Figure 2: Relationship between GDP per capita and the fraction of total inclusive wealth made up by natural capital, excluding minerals and oil. Color shadings indicate the areas with higher densities of data points for each continent. Data from the World Bank Database.

4.2 Utility Function

The production function discussed above describes the dependence of economic production on natural capital. But non-use values of nature, such as existence and bequest values, have long been recognized (Krutilla 1967). Through the production of non-use values, natural capital might also enter directly into utility, providing benefits to people independent of any role in economic production. This section discusses the representation of utility in SCC calculations and particularly how non-market or non-use values enter into utility and determine the welfare consequences of climate change-driven impacts to natural capital.

The utility function plays a critical role in determining the welfare costs of climate change. Climate change impacts are long-lived, uncertain and unequally distributed and there is a substantial literature documenting how parameters of the utility function such as the discount rate, risk aversion, and inequality aversion affect the social cost of carbon (Anthoff & Emmerling 2019; Anthoff et al. 2009; Nordhaus 2007). A much smaller literature, however, has also documented how assumptions regarding the substitutability of goods in the utility function can also have important implications for the welfare effects of climate change.

First described as "intangibles" (Tol 1994) and subsequently as "environmental goods" (Hoel & Sterner 2007) or "non-market goods" (Drupp & Hänsel 2020), the insight from these papers is that some unknown, but potentially large, fraction of climate change damages will fall on non-market goods such as health and mortality, recreation and leisure, or ecosystem goods and services. Assumptions about how impacts to these goods interact with more typical market consumption goods in the utility function can be an important, but often overlooked, driver of results from IAMs.

Although all cost-benefit IAMs that calculate the SCC in principle include a full suite of damages encompassing both market and non-market goods, these are modeled as falling on a single consumption good. In DICE, for example, utility of the representative agent is given by constant relative risk aversion (CRRA) utility:

$$u(c_t) = \frac{c_t^{\eta}}{1-\eta} \qquad \text{Equation 3}$$

Where η is the coefficient of relative risk aversion that parameterizes the curvature of the utility function. Climate change damages through both market and non-market channels are modeled as falling on the aggregate consumption good, *c*. As Sterner and Persson (2008) describe, this assumes perfect substitutability between climate damages and consumption of market goods: "one dollar's worth of climate damages, regardless of the kind, can be compensated by a dollar's worth of material consumption" (p. 68).

Alternate utility functions relax this assumption to allow market and non-market goods to enter the utility function separately. For instance, Tol (1994), Weitzman (2012), and Brooks and Newbold (2014) propose additively separable utility function, in which some damages accrue on a second environmental good, shown as e_t in equation 2:

$$u(c_t, e_t) = f(c_t) + g(e_t) \qquad \text{Equation 4}$$

Brooks and Newbold (2014) are thinking particularly of non-use values of biodiversity and argue this utility value is largely independent of values derived from consumption of market goods and services, in contrast to other use values provided by ecosystems. Weitzman (2012) similarly argues that utility derived from "things that are not readily substitutable with material wealth, such as biodiversity and health" (p. 60) might be captured in this additive term.

Other authors considering two-good utility functions in the context of climate damages, beginning with Hoel and Sterner (2007) and Sterner and Persson (2008), have used constant elasticity of substitution (CES) utility functions given by:

$$u(c_t, e_t) = \frac{1}{1-\eta}(\alpha c_t^{\theta} + (1-\alpha)e_t^{\theta})^{\frac{1-\eta}{\theta}} \qquad \text{Equation 5}$$

Where, as in Equation 1, η parameterizes the curvature of the utility function, θ gives the degree of substitutability between consumption and environmental goods, and α gives the shares of utility arising from the two goods.

Equation 5 includes a number of difficult to estimate parameters. Values used in the literature for θ have ranged widely, from partial complements ($\theta = -1$ in Hoel & Sterner (2007) and Sterner and Persson (2008); $\theta = -0.33$ in Kopp et al. (2012)), to partial substitutes ($\theta = 0.6$ in Bastien-Olvera and Moore, 2021). This value is theoretically related to the income-elasticity of willingness to pay for environmental goods (Baumgärtner et al. 2015; Ebert 2003). Reviews of estimates of these income elasticities reported in the literature suggest consumption goods are weak to moderate substitutes for consumption goods, with θ values roughly between 0.2 and 0.6 (Baumgärtner et al. 2015; Drupp 2018; Drupp & Hänsel 2020).

Figure 3 gives a schematic illustration of how different values of θ determine both utility growth over time and climate change impacts. The underlying model includes constant growth in the consumption good, c_t but no growth in the environmental good, e_t. Even absent climate change damages (solid lines, Figure 3a), the differential growth rates of the two goods interact with θ to produce different utility pathways over time: under complementarity (i.e. $\theta < 0$), the fixed flow of e_t constrains the utility derived from the growing consumption good, c_t resulting in slower utility growth than if the two goods are substitutes (i.e. $\theta > 0$).

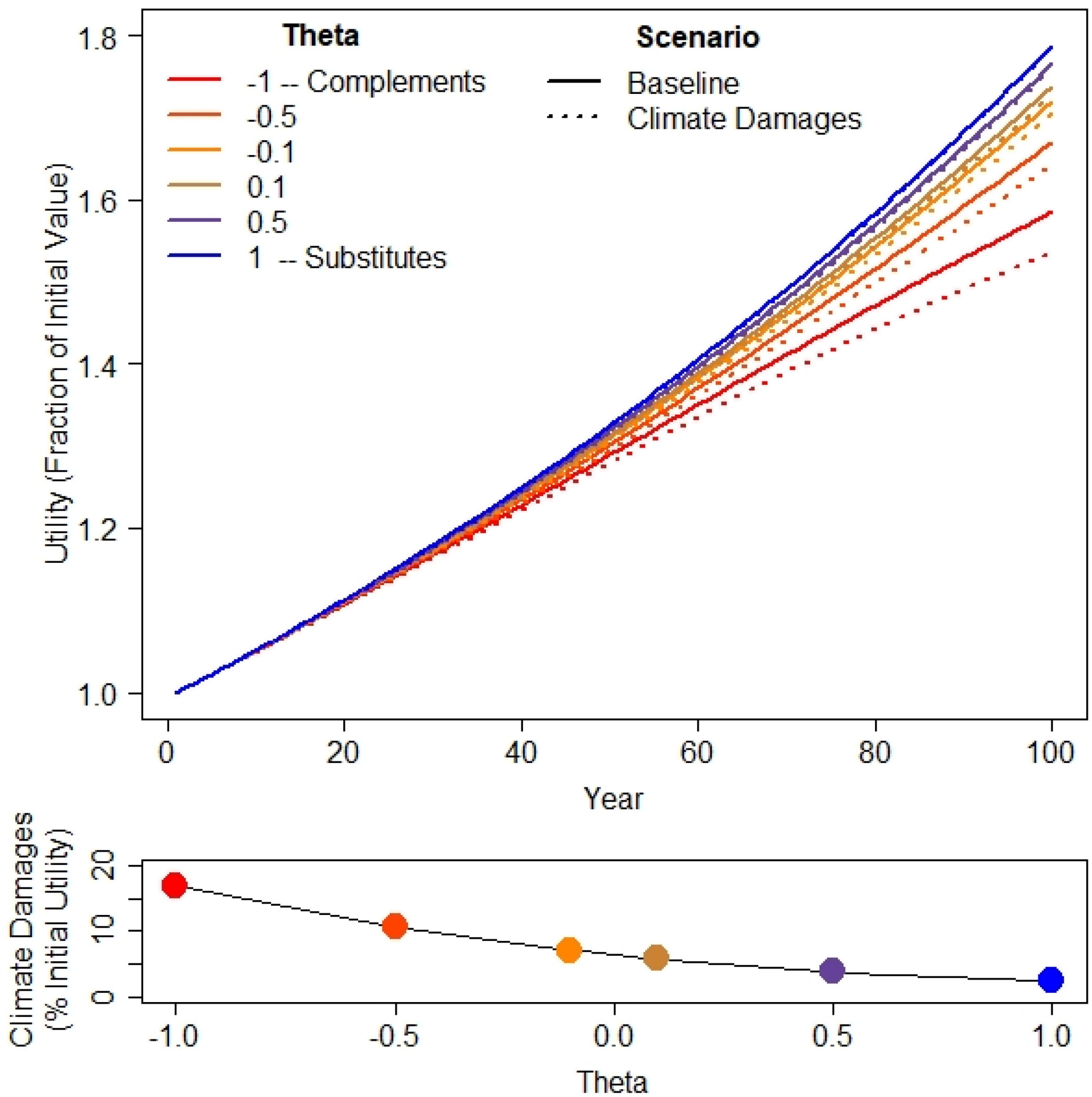

Figure 3: a) Baseline utility growth (solid lines) with a growing consumption good and fixed environmental good and CES utility under different substitutability parameters (θ). Dotted lines show utility growth if the environmental good gradually declines over time due to climate damages. b) Present

value of climate damages shown in a (difference between dotted and solid lines) under a 2% utility discount rate as a function of θ.

Dotted lines in Figure 3a show utility growth if the environmental good gradually declines over time due to climate change damages. Once again, depending on θ, the same changes to the environmental good produce much larger changes to utility (both proportionally and in absolute terms) under complementarity than under substitutability. Figure 3b gives the present value of these damages under a 2% utility discount rate and shows the same biophysical climate impacts (i.e the same reductions in the flow of the environmental good) produce welfare costs 7 times higher under $\theta = -1$ compared to $\theta = 1$. The CES function, as its name would suggest, uses a constant value of θ over the range of environmental goods, which could be a good approximation for small changes in the relative scarcity of different types of goods. It might well be though that the elasticity of substitution falls as the environmental good becomes very scarce, implying much larger marginal climate change damages at low levels of the natural capital stock. This case would also imply an important interaction effect between climate damages and other drivers of ecosystem decline: if other anthropogenic impacts over the 21st century such as habitat loss or air and water pollution cause a substantial diminishment of the natural capital stock with a corresponding decrease in substitutability, then additional losses from climate change will be more damaging than in the absence of those other drivers.

4.3 *Damage Function*

Section 3 discussed evidence from the ecological literature on how climate change is likely to alter ecosystem productivity and raise extinction risk for many species. These damages all ultimately have implications for the contributions of natural systems to human welfare, as shown in Table 1. These services range from market goods such as timber and fish production, non-market goods such as storm protection or recreational opportunities, and non-use values such as existence and bequest values.

Capturing these changes in SCC calculations requires valuing their effects in order to parameterize a damage function relating global (or regional) changes in temperature with effects on human welfare via ecological changes. Changes in non-market goods and services can be valued using standard valuation tools in environmental economics such as travel-cost or hedonic approaches. For instance, studies of recreation in the US suggest outdoor recreation decline at higher temperatures, though with substantial opportunities for intra-day substitution (Chan & Wichman 2020; Dundas & von Haefen 2020), while Kovacs et al. (2011) show persistent declines in property values near areas affected by mass tree mortality. Moore et al (Moore et al.) estimate changes in species listing and spending under the Endangered Species Act due to climate change, bounding one aspect of climate change effects on extinction risk (i.e. increased conservation spending).

These kinds of empirical studies tend to be focused on limited geographic areas with large volumes of data, typically in a small number of wealthy countries. Because CO_2 is a global pollutant though, SCC calculations require geographically comprehensive estimates of damages. Only a couple comprehensive global damage functions for the ecological impacts of climate change exist, mostly associated with the FUND IAM (Anthoff & Tol 2014; Tol 2002). As discussed in Section 1, FUND includes damage functions for 12 types of climate change impacts, including two related to natural capital: a reduction in ecosystem services from wetlands due to sea-level rise, based on a meta-analysis of ecosystem service valuations of wetlands by Brander et al. (2006), and an ecosystems damage function capturing non-use values of biodiversity decline.

Brooks and Newbold (2014) present a revised biodiversity loss damage function using updated ecological estimates of species loss with global warming, with valuation based on a stated-preference study (Kramer & Mercer 1997) and a meta-analysis of stated willingness to pay estimates (Richardson & Loomis 2009). They find much larger welfare effects of biodiversity decline than currently included in FUND due to both higher projected effects of warming on biodiversity and an alternate biodiversity value function. Finally, Brander et al. (2012) also provide an ocean acidification damage function, based on a similar approach to the wetland damage function in FUND using a meta-analysis of published ecosystem service values, but this has not been implemented in IAMs or contributed to SCC calculations.

However, Fenichel et al. (2016b) point out that a full valuation of changes in natural capital depends on institutional arrangements that manage the stock and determine the economic and behavioral response of actors to climate-change induced shifts in ecosystem productivity. Because most ecosystem goods are either public goods or common pool resources, one cannot assume optimal management, as might hold under a privately owned resource (Fenichel & Abbott 2014). They give the example of an open access fishery where, because rents are competed away, no wealth is preserved in the fish stocks by long-term management institutions and therefore climate change can not affect the value of the natural capital stock. In contrast, climate-induced shifts in the distribution or productivity of non-open-access fisheries will have implications for the natural capital stock, but will depend on the interaction of biophysical changes with the management institutions and the price function (Fenichel et al. 2016b). Damage functions that incorporate these institutional and price effects are still missing from the literature.

One issue to consider in modeling the costs of climate change's ecological impacts is the degree to which temperature change is best thought of as affecting a stock of natural capital or a flow of ecosystem services. Damages to the natural capital stock permanently reduce the flow of ecosystem services unless the stock is restored, whereas damages to the flow of ecosystem services produce impacts contemporaneously but not in future years (see Dell et al. (2012) for a discussion related to market climate change impacts). Different types of ecological changes could best be thought of as stock vs flow impacts: CO_2 fertilization affects the productivity of the existing forest stock for example and might best be thought of as a flow impact, whereas extinctions, forest dieback and wetland loss have long-lived impacts on the flow of ecosystem services from ecological systems and might best be thought of as stock impacts. These could be explicitly modeled explicitly as impacts to a natural capital stock, as in Bastien-Olvera and Moore (2021), or parametrized as a more typical IAM damage function falling on contemporaneous production, but calibrated using the present value of the stream of lost ecosystem services (as in the wetland damage function in FUND or in Brooks and Newbold (2014)).

To date, most of the literature has considered the direct welfare costs of climate change effects on natural systems, but there are likely to be indirect effects too. For instance, climate change will lower the productivity of agricultural production in many areas, possibly driving agricultural expansion into natural areas with associated loss of habitat and ecosystem services. Piontek et al. (2021) used a CGE model combined with species-distribution modeling to estimate the magnitude of these indirect effects on bird species in Vietnam and Australia. They find the indirect effects in this setting to be small relative to the direct effects of climate change on species habitat. A fuller accounting might also consider loss of productive agricultural land due to sea-level rise, such as in low-lying river deltas.

A final issue related to modeling climate change damages in SCC calculations relates to the question of adaptations that might limit the adverse consequences of climate change. In general, climate damages should be calculated net of adaptations, i.e. including both the residual damages from climate change after adaptation and the adaptation costs (Cropper & Oates 1992). For many sectors both the benefits and costs of adaptation are borne by those making the decision, meaning there are no externalities to the decision and, barring other market failures, we would expect optimal levels of adaptation to happen privately or autonomously (Hertel & Lobell 2014; Mendelsohn 2000). Farmers facing increased drought or homeowners experiencing uncomfortably warm temperatures, for example, incur both the benefits and costs of adaptive actions such as installing irrigation or air-conditioning. Ecosystem damages though are different in that many adaptations are public goods and will be undertaken by governments. Although there is currently substantial discussion about the role natural resource managers and conservation agencies might play in adapting to climate change (Bradford et al. 2018; Dudney et al. 2018; Tittensor et al. 2019), the aggregate costs and effectiveness of these actions – and therefore the net benefits of adaptation – are still not well quantified.

In understanding climate change damages, it is important to note that while climate change is becoming an increasingly powerful driving force of ecological change, other human-caused mechanisms of ecosystem degradation currently exert more pressure on natural systems (Venter et al. 2016). For instance, conversion of ecosystems to cropland, pastures and rangelands has been the major factor of biodiversity loss, habitat fragmentation, and disruption of water and nutrient cycles (Foley et al. 2005). In addition, resources extraction, invasive species and pollution are direct driving forces that affect ecosystems (Brondizio et al. 2019). These other mechanisms are closely related with modes of economic production, environmental regulations, and will co-evolve with climate change impacts over the 21st century. A complete picture of climate damages on ecosystems and its consequences for human wellbeing must include these parallel but interrelated damage pathways.

5. Conclusion

Human wellbeing depends partly on functioning ecosystems that provide inputs to the production of market and non-market goods, as well as pure existence and bequest values. Climate change over the next decades and centuries will profoundly re-shape natural systems changing, and in many cases reducing or disrupting, the flow of these benefits. Understanding how these changes affect aggregate estimates of the climate change costs like the social cost of carbon is complex. It requires not just projecting the biophysical and ecological changes projected with a warmer planet – an active area of work within ecology and where large uncertainties still remain – but also modeling the dependence of economic production and human welfare on these systems. Given the difficulty of estimating non-market and, particularly, non-use values, this almost certainly presents even greater empirical and modeling challenges.

Exactly how natural capital enters into the production and utility function has potentially large implications for the welfare effects of ecological climate impacts. But many of these parameters are still not well understood and these questions speak to long-standing and still unresolved debates within economics regarding the substitutability of resources, land, or natural capital more generally in the production of consumption goods and human welfare.

It is also important to note that climate change is only one of many threats to biodiversity and well-functioning ecosystems over the 21st century and beyond. Other externalities from economic activity such as habitat destruction, pollution, or over-exploitation present larger threats to the natural capital stock than climate change. These effects will interact with climate change to determine the trajectory of natural systems in the anthropocene. Climate change damages on natural capital therefore also need to be situated in this larger context of other market failures and evolving governance structures.

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