Towards a more inclusive and precautionary indicator of global sustainability

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ABSTRACT

We construct a hybrid, economic indicator of the sustainability of global well-being, which is more inclusive than existing indicators and incorporates an environmentally pessimistic, physical constraint on global warming. Our methodology extends the World Bank's Adjusted Net Saving (ANS) indicator to include the cost of population growth, the benefit of technical progress, and a much higher, precautionary cost of current CO_2 emissions. Future warming damage is so highly unknowable that valuing emissions directly is rather arbitrary, so we use a novel, inductive approach: we modify damage and climate parameters in the deterministic DICE climate-economy model so it becomes economically optimal to control emissions in a way likely to limit warming to an agreed target, here 2 ^{o}C. If future emissions are optimally controlled, our ANS then suggests that current global well-being is sustainable. But if emissions remain uncontrolled, our base-case ANS is negative now and our corresponding, modified DICE model has an unsustained development path, with well-being peaking in 2065. Current ANS on an uncontrolled path may thus be a useful heuristic indicator of future unsustainability. Our inductive method might allow ANS to include other very hard-to-value, environmental threats to global sustainability, like biodiversity loss and nitrogen pollution.

Keywords: global sustainability; optimism and pessimism; precautionary valuation of CO_2 emissions; unknowability and induction; population growth; technical progress

1. Introduction

Are current levels of global human well-being sustainable for at least a century, if depletion of the planet's environmental resources is optimally controlled in future? Is rising global well-being *un*sustainable for another century or so, if business-as-usual trends in largely uncontrolled depletion of environmental resources continue? Asking these two questions about global sustainability tackles one of humanity's most complex and persistent debates, where most contributions (e.g., Meadows et al., 1972; Nordhaus, 1973) belong to one of two opposing paradigms (Neumayer, 2013). The first paradigm can be broadly labeled "substitutability" (of human-made inputs for environmental resource inputs in producing output and well-being), "weak sustainability",[1] or "environmental optimism", though these labels do not have identical meanings. The second can be broadly labeled "non-substitutability", "strong sustainability", or "environmental pessimism". A key reason why they persistently disagree is that "support for one paradigm or the other depends much on basic beliefs ... that are non-falsifiable and cannot therefore be conclusively decided" (Neumayer, 2013: 3). We therefore use "optimism" and "pessimism" here purely non-judgmentally, just to describe the paradigms.

Because of these non-falsifiable disagreements, some authorities recommend informing policy debates by presenting multiple sustainability indicators from different paradigms (e.g., Stiglitz et al., 2009). As an alternative, we make a first attempt at developing here a single, policy-relevant, empirical indicator of global sustainability, that is more inclusive than existing indicators in three ways. First, it includes more determinants of global sustainability than have yet been combined in any single indicator. Second, it includes elements of both optimistic and pessimistic paradigms, and so in some sense attempts to bridge the gulf between them in order to better inform policy-makers, who cannot subscribe to different planets like academics subscribe to different paradigms. Third, our indicator can be applied to both our

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[1] An even "weaker" paradigm is mainstream growth economics, which almost completely ignores environmental resources. For instance, only one paper (Brock and Taylor, 2010) out of 121 during 2004-13 in the prestigious *Journal of Economic Growth* considered global warming or energy inputs.

opening questions, about global sustainability under optimal control, or under negligible future control, of the environment.

Our focus on building a single, inclusive, and policy-relevant indicator leads us to use a novel, experimental methodology, which is perhaps more the contribution of this paper than the particular numerical results shown here. We change and extend the empirical indicator of global sustainability that is already most inclusive and policy-relevant. This is the global result for the World Bank's Adjusted Net Savings (ANS, also known as Genuine Saving) indicator, which the Bank estimates for over 120 countries (World Bank, 2006, 2011). Derived from conventional, "weak" economic theory, ANS estimates how well any society is currently maintaining all its human-made and natural assets. ANS assumes smooth substitutability among and optimal control of all inputs, which allows it to serve as a sustainability indicator, albeit an inexact one (Hamilton, 1994; Hamilton and Clemens, 1999; Pezzey, 2004), where sustainability is defined as society being able to sustain current, average well-being indefinitely (Pezzey, 1997). Our global use of this definition inherently ignores the requirement for more equity within and between nations that many authors consider a vital part of sustainable development, and avoids the need to consider international trade. We also ignore possible non-environmental impacts on long-run global well-being, such as from nuclear war, disease, or asteroids.

Data and computational limits mean that the World Bank does not estimate each country's ANS from a separate, complete empirical model for that country. Instead, each estimate is a hybrid: it adds together direct valuations from different sources, using market-based prices (including discount rates) if available, and modeling results if not, a process which inevitably entails broad approximations and many omissions. Our indicator hybridizes World Bank ANS further, by replacing its (weak, optimistic) valuation of the current CO_2 emissions causing future global warming with much higher, precautionary valuations. We calculate these valuations by backwards *induction* from a physical (strong, pessimistic) target of limiting warming to the globally agreed Copenhagen 2 ^{o}C limit (UN, 2009). However, discount rates in our inductive method are still market-based and very similar to the World Bank's. In that sense we are interpreting the 2 ^{o}C limit as meaning the aim of climate policy is to protect future generations from global warming damage, rather than to increase general intergenerational concern. The second interpretation merits further research but is beyond our scope here.

In addition to changing the World Bank's CO_2 valuation for ANS, we also extend their ANS by including fairly conventional estimates of the cost of exogenous population growth, currently not reported globally, and the benefit of exogenous technical progress, currently omitted. According to these estimates, the sustainability cost of population growth, assumed to be at a constant rate, is generally outweighed by the sustainability benefit of technical progress. Our modifications to ANS are thus not a uniform shift towards environmental pessimism. And our two extensions would be impossible to make with pessimistic, biophysical, "strong" indicators of global environmental impacts, such as the Ecological Footprint or Living Planet Index (e.g., WWF, 2012), Human Appropriation of Net Primary Production (e.g., Krausmann et al., 2013), or Energy Return On Investment (e.g., Gagnon et al., 2009). These were never designed to include all determinants of well-being, and cannot be extended to do so.

As detailed later, our precautionary, inductive method for revaluing CO_2 emissions entails finding parameters for climate damage, climate sensitivity, and non-CO_2 radiative forcing that will, in a deterministic, integrated assessment (global climate-economy) model (IAM), make it economically optimal to control emissions enough to be likely (give about a two-thirds chance, reflecting moderate risk aversion) to limit peak global warming to 2 ^{o}C.[2] The IAM we use is a modified version of DICE-2007, Nordhaus's (2008) version of his Dynamic Integrated model of Climate and the Economy, hereafter DICE or standard DICE unless ambiguity arises. Inductive approaches have been used before in climate economics to induce model parameters from policy goals, for example by Gjerde et al. (1999), though they included the well-being (pure time) discount rate as one of the parameters induced.

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[2] Other warming limits could readily be used with our approach, and may need to be, given the ever-increasing difficulty of staying within 2 ^{o}C (e.g., Guivarch and Hallegatte, 2013).

Running the base case of our inductively modified DICE model with either optimal control or no control of CO_2 emissions then yields two very different social costs of current CO_2 emissions (SCCs): $131 per ton of carbon (/tC) under optimal control, and $1,455/tC under no control, where "$" always means US2005$. These are much higher than DICE or World Bank SCCs; but our no-control SCC is exceeded by some in the economics literature (e.g., ~$94,000/tC in Howarth et al., 2014), and by the infinite SCC implied by the absolute "non-substitutability" language used in most "strong sustainability" literature. Our modified DICE also yields two valuations of technical progress, and inserting these and our SCCs (CO_2 valuations) into an extended World Bank ANS addresses, though unsurprisingly does not answer conclusively, our two opening questions about global sustainability.

Throughout the paper we discuss the validity of different parts of our methodology. In particular, our use of induction in a deterministic IAM to revalue CO_2 emissions is contentious enough to warrant extensive discussion below, with a summary here. We judge that the World Bank's SCC of $24.5/tC is inconsistent with recent warnings from climate scientists about dangerous global warming, and so should be replaced with a more precautionary value. But we depart from the conventional view that economic modeling should be used to estimate directly how much warming should be permitted, because of a second judgment, that climate damage is *highly, but not absolutely, unknowable*, especially at high warming levels. All climate damage functions in existing IAMs therefore use essentially arbitrary guesswork at high warming levels. So inducing an SCC from the knowledge inherent in the consensus 2 ^{o}C target is not necessarily any less coherent, and is worth trying as an alternative. And our somewhat paradoxical use of a deterministic IAM, despite high unknowability, makes our key assumptions easier to find and contend than if we used a more complex, probabilistic IAM.

Inductive valuation also opens the important possibility of including in ANS other "strong", physical limits to global sustainability, such as "planetary boundaries" for biodiversity loss or for human conversion of atmospheric nitrogen to reactive forms, about which Earth system scientists have expressed great concern (Rockstrom et al., 2009), but whose dollar value is also highly unknowable. Our approach can thus also be seen as a new hybrid sustainability indicator which applies the concept of Critical Natural Capital globally, to add to the rather different hybrids reviewed by Dietz and Neumayer (2007).

Other inductive methodologies and other models could of course have been chosen, and will be discussed briefly later. A broader, non-inductive and altogether more ambitious alternative would be to set aside the World Bank's ANS and develop a fuller, unified empirical model of global development, perhaps by adding minerals and energy depletion, various uncertainties and other features to DICE, and then using this fuller model to directly forecast well-being and sustainability. We do not attempt this for two reasons. First, it would require much further research, well beyond our scope here, and a climate damage function would still have to be guessed somehow. Second, by modifying the World Bank's ANS, we address policy-makers more directly than by deriving an ANS solely from an academic model. Overall, we contend that our hybrid, "weak/strong" approach, the first to include exogenous technical progress and an environmental constraint in a single-number indicator of the sustainability of global well-being, is an experiment well worth trying, in keeping with the transdisciplinary and methodologically open spirit of this journal.

We proceed as follows. Section 2 notes opposing views on the importance of CO_2 emissions, and explains further why we use induction to replace the World Bank's CO_2 valuation. Section 3 summarizes the theory of ANS, the current empirical practice of World Bank ANS, and literature stemming from Dasgupta and Mäler (2000) that uses an alternative, instantaneous definition of sustainability. Section 4 explains why we chose DICE-2007 instead of another IAM, how we modified it inductively to give our precautionary CO_2 valuations, and how we included population growth and technical progress in ANS. Section 5 gives our modified ANS results and sensitivity testing. Section 6 considers whether our inductive approach might be used to include other global environmental threats, like biodiversity loss and atmospheric nitrogen conversion, in ANS. Section 7 concludes.

2. The case for an inductive, precautionary valuation of the social cost of CO_2

2.1. Optimistic versus pessimistic views on the importance of CO_2 emissions

The World Bank (2011: 78) reported the wide range of SCCs found by Tol's (2005) survey, from −9.5 to 350 US2005$/tC at his 5th and 95th percentiles respectively. The World Bank then chose an SCC of $24.5/tC, based on Fankhauser (1994), which values CO_2 emissions during 1975-2008 at 0.4-0.5% of global gross domestic product (GDP). This small value appears in Fig. 1 as the narrow gap between the two graphs for global ANS during this period, which ignore or include the CO_2 deduction. As noted below in Section 4.1, $24.5/tC is close to DICE's optimal SCC and is a key reason for our choosing DICE. It is thus also consistent with DICE's associated, non-optimal scenario, where warming reaches 6.1 ^{o}C if emissions remain uncontrolled for 250 years, yet average well-being, our term for Nordhaus's (2008: 39) "generalized consumption per person", still grows 19-fold, to only ~10% less than the hypothetical 21-fold growth that would occur without the resulting climate damage.

Such minimal projected damage to well-being is in stark contrast to increasingly strong warnings by climate scientists about dangerous global warming (e.g., Hansen et al., 2008, 2012; Smith et al., 2009), and also to the importance of CO_2 suggested by the pessimistic, "strong sustainability" indicators in Fig. 2. These show the trends of global Ecological Reserve – defined as [Biocapacity minus Ecological Footprint] divided by Biocapacity, and also known as "ecological overshoot" when negative – ignoring or including deductions for CO_2 emissions (the Carbon Footprint). The popular and influential Ecological Footprint adds up "the area required to produce the resources people consume [and] the area occupied by infrastructure" (WWF, 2012), so Ecological Reserve does not claim to be a society-wide sustainability indicator, and is not quantitatively comparable with ANS. Nevertheless, both indicators claim to indicate unsustainability when negative, so they are comparable in terms of sign and trend, and to that extent they disagree strongly. We next consider in detail the difficulty in resolving scientifically such deep disagreements about the importance of CO_2 to sustainability.

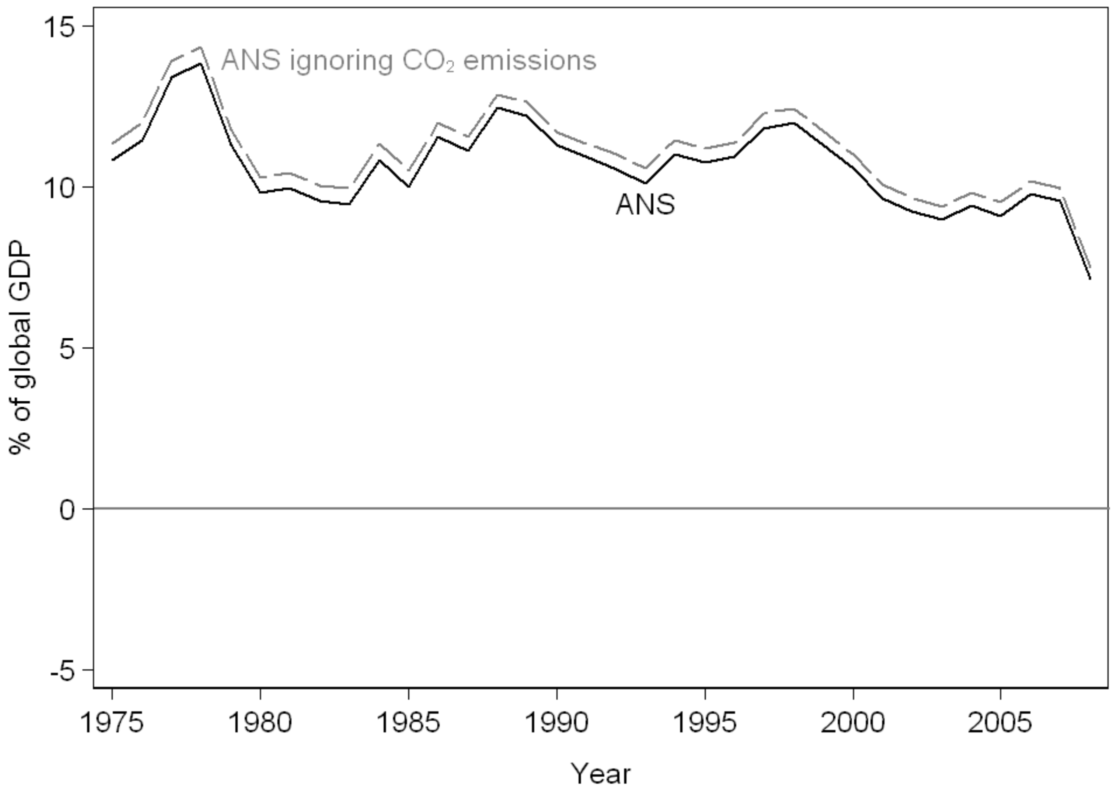

Fig. 1. Global Adjusted Net Saving (ANS), 1975-2008. Both series exclude small deductions for particulate emissions. Source: World Bank (2013).

2.2. The high unknowability of future climate damage, and the case for our inductive valuation of CO_2 emissions

Since at least the seminal work of Funtowicz and Ravetz (1991), many writers about global, long-term environmental issues have stressed the deep uncertainties involved, and the resulting difficulties for analyzing such issues using normal scientific methods. But explicit discussion of the fundamental obstacles causing such uncertainties is rare (e.g., by Baer and Risbey, 2009). We highlight them here to support our view that future climate damage is, and will very probably remain, unknowable to a high enough degree to justify valuing CO_2 emissions inductively, so as to make use of the limited information embodied in the agreed, known 2 ^{o}C target.

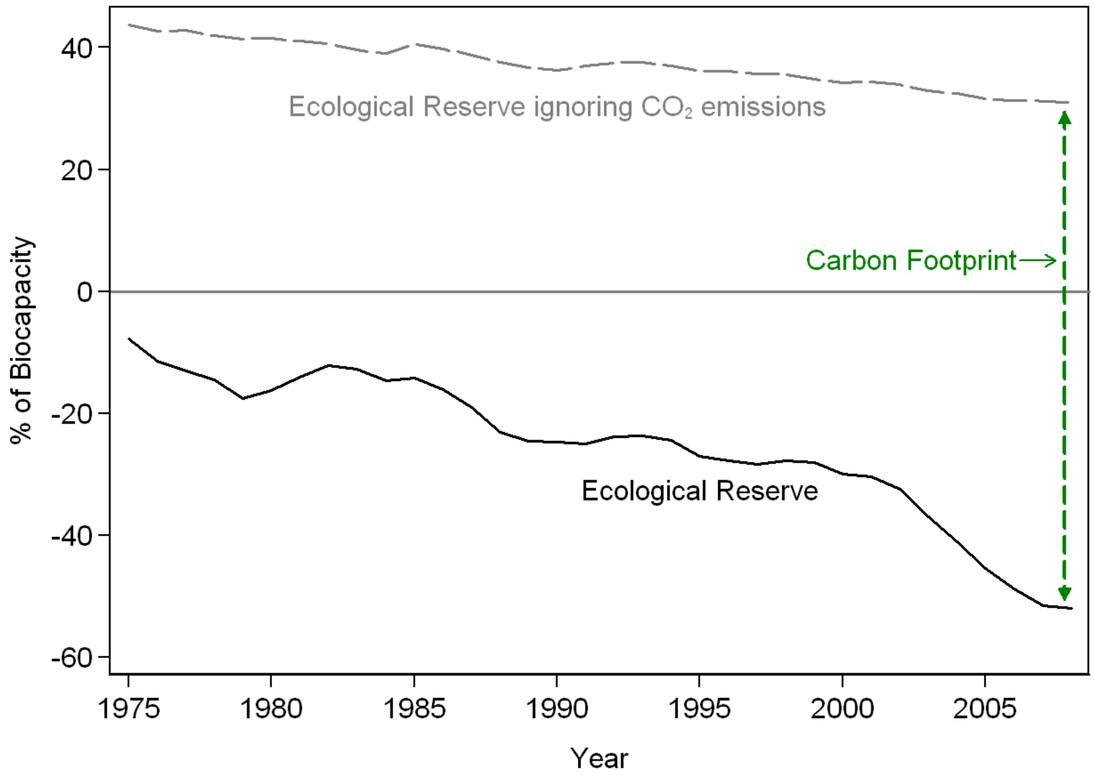

Fig. 2. Global Ecological Footprint data shown as Ecological Reserve, 1975-2008. Source: Global Footprint Network (www.footprintnetwork.org).

Because the Earth is unique in its complex geophysical and biological systems, controlled global experiments are impossible. Comparisons with Venus's greenhouse effect, palaeoclimatic studies, and natural experiments like volcanic eruptions, can all provide important insights into the Earth's climate system, but cannot definitively constrain its future behavior. Humanity's disturbances to the Earth's systems continue at unprecedented levels (Steffen et al., 2004), and their final effects will not be known for centuries, if only because of the thermal inertia of oceans and ice-sheets (Lenton et al., 2008; Richardson et al., 2011). Modeling future physical changes in climate thus strains normal scientific methods to the limit; but estimating future climate damage also needs to gauge the interaction of physical changes with an unprecedented human population. History is of limited use: the growing evidence of severe impacts of climate change on past societies (e.g., McMichael, 2012) cannot yield a monetary estimate of future climate damage in a globalized economy with 8 or 9 billion people. Thus uniqueness, complexity, centuries-long time delays and the human dimension combine to generate severe, scientifically unresolvable (non-falsifiable) disagreements about estimating future climate damage, which are very unlikely to be much reduced by learning over coming decades.

Our specific focus here is on disagreements about the damage function, when defined as the proportion ω of global economic output lost by contemporaneous global warming of T ^{o}C above the pre-industrial global temperature, or its complement, the net-of-damage function $\Omega(T)$. A common formula, used here, is

$$\omega(T) := 1 - \Omega(T) = aT^N / (1 + aT^N); \quad a, N > 0. \tag{1}$$

There are many disagreements about other climate parameters, notably climate sensitivity (the equilibrium global warming caused by doubling greenhouse gas concentration, e.g., Weitzman, 2009, 2012), and growing criticisms of the assumption in (1) that damage depends only on contemporaneous warming (e.g., Stern, 2013; Cai et al., 2013). However, disagreements about $\omega(T)$ form our main reason for using induction.

Conventional IAMs, including that in Stern (2007), use optimistic $\omega(T)$'s, estimated for a given warming (typically 2.5 or 3 ^{o}C) and then extrapolated, often using an assumed quadratic form, to much higher temperatures (Tol, 2009; Aldy et al., 2010). This yields direct disagreement with more pessimistic $\omega(T)$'s at “super-extreme” and “extreme” warming (say $T \approx 12$ and $T \approx 6$). For example, DICE’s

$$\omega(T) = 0.0028388T^2 / (1 + 0.0028388T^2) \tag{2}$$

(Nordhaus, 2007) has $\omega(12)$ = 29% and $\omega(6)$ = 9%, whereas Weitzman (2012) has $\omega(12)$ = 99% and $\omega(6)$ = 50%. Disagreement among economists about $\omega(T)$ at merely “high” warming (say $T \approx 3$) is less marked. Nevertheless, most non-economist supporters of a 2 ^{o}C warming limit still regard 3 ^{o}C as very dangerous; yet DICE’s $\omega(3)$ is only 2.5%, close to the best-fit values estimated in Tol’s (2009, 2012) meta-analyses of 13 other models, and equal to only around one lost year of consumption growth.

Can elicitation of expert judgment settle such disputes? Expert elicitation is often used to make subjective estimates of probabilities of future outcomes in climate science, for example by Lenton et al. (2008) and Kriegler et al. (2009) for a range of climate tipping points; but its only application to climate damage was by Nordhaus (1994).[3] His results were used for calculating DICE's expected value of climate catastrophe, and for example by Mastrandrea and Schneider (2004) to construct a damage probability distribution. His study had only 19 participants from three high-income countries and has not been repeated, so it would need updating and improving – and would still face the fundamental obstacles already noted – if expert elicitation is to play any future role in climate damage estimation.

Given this lack of data, all IAMs so far have had to use guesswork as the basis for damage functions at higher temperatures. Dietz et al.'s (2007: 314-5) parameters for both non-catastrophic and catastrophic climate damage were "essentially assumed" or "genuine guesstimates". Ackerman et al. (2010) used $\omega(T) = .0028388T^N / (1+.0028388T^N)$ with N ranging stochastically from 1 to 5, but they called this choice, and DICE's $N = 2$ in (2), "arbitrary" and "fact-free" because "there is essentially no relevant empirical research" (p. 1662). Similar language occurs in Dietz (2011: 523), Weitzman (2012: 234) and Dietz and Asheim (2012: 328), and supports a stronger criticism that directly estimated IAM damage functions "are completely made up, with no theoretical or empirical foundation" (Pindyck, 2013: 870). The problem is unavoidable, though not explicitly discussed, even in the most sophisticated recent probabilistic models, for example in Cai et al. (2013), who show the large effect on SCCs of both risk aversion and irreversible shocks in climate damage. For although probabilistic IAMs typically include uncertainty in the damage function, they still face the high unknowability of the function's probability distribution. We conclude that estimating a precautionary valuation of CO_2 by backwards, deterministic induction from a globally agreed warming limit like 2°C is not in principle any less coherent or more contentious than direct, probabilistic valuations which cannot avoid using rather

[3] Weitzman (2012) cited Kriegler et al.'s expert elicitation of probabilities for climate tipping points as rough evidence for his choice of $\omega(6)$, but such evidence that $\omega(6) = 50\%$ instead of, say, 30% or 70%, is very indirect.

arbitrary guesswork for key parameters, and is worth exploring as an alternative way of dealing with underlying non-falsifiability. Using a CO_2 valuation induced from a "strong" warming limit might also give our modified ANS indicator more credibility with some sustainability pessimists and environmental policy-makers.

Such induction can, however, use many different methods and/or models. In particular, some readers may find implausible our assumption that a 2 ^{o}C warming limit is optimal under standard discount rates. Many IAMs have instead assumed higher intergenerational concern than implied by standard discounting, for example as lower discount rates in Stern (2007), or as an ethical constraint like Dietz and Asheim's (2012) Sustainable Discounted Utilitarianism. An alternative would thus be to vary such concern, but not DICE's damage function, inductively to find what makes a given warming limit optimal. As noted earlier, this alternative deserves further research, but here we focus on higher climate damage and keep the World Bank's practice of using market prices, including discount rates, where possible.

A complementary alternative, also deserving further research, would be to use induction in recent, probabilistic IAMs like Dietz and Asheim (2012) and Cai et al. (2013).[4] This could include risk aversion directly, rather than indirectly by our precautionary recalibration of standard, deterministic DICE, and these models' results can depart significantly from deterministic models'. But such complex models are at the frontiers of what is computationally possible, so adding induction would make tractability challenging. Our use of a simpler, deterministic model also allows a sharper focus on why and how we use induction to tackle the high unknowability of climate damage.

Irrespective of whether alternative, precautionary CO_2 valuations are found directly or inductively, using them to replace the existing valuation in World Bank ANS raises further questions about our methodology, addressed at the end of the next subsection.

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[4] Also Howarth et al (2014), if its saving and emissions control rates are endogenized so that optimal control paths can be found.

3. Theory and practice of Adjusted Net Saving (ANS)

3.1. Theory

As currently estimated by the World Bank (2011, 2013), ANS for a geographical region is:

$$\text{basic ANS} = P_1\dot{K}_1 + P_2\dot{K}_2 + ... + P_j\dot{K}_j =: \mathbf{P}.\dot{\mathbf{K}}, \tag{3}$$

usually reported as a percentage of output, to make results comparable across time and regions. Here $(\dot{K}_1, \dot{K}_2, ..., \dot{K}_j) =: \dot{\mathbf{K}}$ are the region's net investments (rates of change over time t, with $\dot{K}_i \equiv dK_i / dt$) in j stocks of manufactured, human, knowledge, and foreign capital, and of environmental resources (also known as natural capital), whose use affects the possibilities for human well-being. $(P_1, P_2, ..., P_j) =: \mathbf{P}$ are rental prices, which measure the social benefits (discounted dollar values over the rest of time, some of them negative, i.e. costs) of unit net investments now in each stock; and the assumption of smooth substitutability, no matter how limited, means that all prices are in principle finite. So **K** includes both economic (owned) stocks like manufactured capital and fossil fuels, where rental prices P_i can be estimated from market prices; and environmental (unowned) stocks like CO_2, where shadow rental prices must be estimated by environmental economists, with difficulties in estimating the valuation P_i for CO_2 already discussed above.

By allowing for exogenous population growth and technical progress, subject to many restrictive conditions, Pezzey (2004) proved a one-sided theoretical link between an extended form of ANS and sustainability in an "optimal" economy: one which maximizes welfare $W\{L(t)u(t)\}$ over the entire future, where $L(t)$ is population and $u(t)$ is well-being (utility) per person. If n is the (constant) rate of population growth, $x(t)$ is the per-person benefit of future, exogenous technical progress that results just from time passing, * denotes optimal values, and $u^m(\mathbf{K}(t))$ is the maximum utility sustainable forever starting from capital stocks $\mathbf{K}(t)$, the link is that:

$$\text{extended ANS} := \underbrace{\mathbf{P}(t).\dot{\mathbf{K}}^*(t)}_{\text{basic ANS}} \underbrace{- n\mathbf{P}(t).\mathbf{K}^*(t)}_{\text{deduction for exogenous population growth}} \underbrace{+ L(t)x(t)}_{\text{addition for exogenous technical progress}} \leq 0$$

$$\Rightarrow \underbrace{u^*(t)}_{\text{current utility}} > \underbrace{u^m(\mathbf{K}^*(t))}_{\text{maximum sustainable utility}} \tag{4}$$

i.e., economy is unsustainable at t.

(See Appendix A for details.) However, current, extended ANS being positive does not mean current well-being is sustainable. The intuition for this one-sidedness is that optimality entails no concern for sustainability as defined here. Indeed, optimality may directly cause an unsustained development path if non-renewable resource depletion is essential for an economy (Dasgupta and Heal, 1974; Pezzey and Withagen, 1998); and high optimal resource depletion rates, $\dot{K}_i$, can drive optimal rental prices P_i (estimated from observed market prices) far below their "sustainability prices" (Pezzey and Toman, 2002).

Among the key restrictions needed for (4) to hold (again see Appendix A) are that n is exogenous and constant, as just noted; u depends only on per-person levels, $\mathbf{C}/L$, of an extended consumption vector $\mathbf{C}$; and the economy's production possibilities have constant returns to scale. All these restrictions are inevitably broken by real-world conditions. The population growth rate "is not and cannot be" forever constant in practice (Arrow et al., 2003).[5] The effect of any public, environmental good in $\mathbf{C}$ on individual well-being u is not diluted by growth in population L. Globally important environmental resources do not exhibit constant returns to scale, because

[5] We find later that in our modified DICE, average well-being falls far below its optimal path when emissions are uncontrolled, so one might expect this to affect population. However, underlying growth in productivity means that well-being stays forever above its initial, 2005 level even on the uncontrolled path, thus giving no reason to suppose that starvation would check population growth. So it is unclear if uncontrolled emissions would lower, or raise, population in a more detailed model with endogenous population.

the global environment cannot be replicated.[6] Nevertheless, (4) is the only known theoretical connection between extended ANS and our sustainability definition.[7] The population term *n***P.K** in (4) is the "Malthusian term" already calculated in World Bank (2006, Appendix 4; 2011, Appendix E) for selected countries, but not connected directly to sustainability or added up globally. There is no good, practical alternative to the World Bank's calculation method, reviewed in Section 4.3 below. That subsection and Appendix B also explain how we calculated the technical progress term *x*. *Lx* was once estimated to add about 40 percentage points of output to US ANS (Weitzman, 1997), a large result which motivates its inclusion here.

Further questions, more specific to this paper's methodology, arise from our insertion below into World Bank ANS of the two very different SCCs derived from optimal and no-control runs of our modified DICE. All observed prices and quantities used in World Bank ANS come from economies that are essentially uncontrolled with regard to the global natural environment. So our result that the no-control SCC is far greater than the optimal SCC means that some optimal, non-CO_2 prices and quantities must be rather different from observed prices and quantities, which reduces the accuracy of our estimate of optimal ANS. As for uncontrolled ANS, this has no formal theoretical link with sustainability, given the optimality needed for (4) to hold, so it can be regarded as only a heuristic indicator of global sustainability. But there is no alternative sustainability theory available to avoid these shortcomings, which are quite unrelated to our use of induction, and would arise from using SCCs from any other IAMs with widely different optimal and no-control SCCs.

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[6] Also, constant returns to scale requires that one can assign meaning to a zero capital stock for each K_i, which is effectively impossible for knowledge and environmental stocks. We thank a referee for noting this, and the previous point on population endogeneity.

[7] Both Arrow et al. (2003) and Asheim (2004) gave formulae for extended ANS when the population growth is not constant, but both omitted the non-autonomous case and gave no connection to sustainability as defined here.

3.2. World Bank practice

The World Bank uses no formal, explicit definition of sustainability, but seems to use the definition in (4), judging by the following: "The rule for interpreting ANS is simple: if ANS is negative, then we are running down our capital stocks and future well-being will suffer; if ANS is positive, then we are adding to wealth and future well-being" (World Bank 2011: 19). This statement overlooks the one-sidedness of result (4). It also overlooks the fact that if wealth is viewed as **P.K**, the value of an economy's entire stocks, then the change in wealth over time is $\mathbf{P}.\dot{\mathbf{K}} + \dot{\mathbf{P}}.\mathbf{K}$, that is, ANS, $\mathbf{P}.\dot{\mathbf{K}}$, plus the capital gains $\dot{\mathbf{P}}.\mathbf{K}$ resulting from real price changes $\dot{\mathbf{P}}$. But despite these oversights, the Bank's sustainability motivation for measuring ANS is clear.

Table 1 lists the World Bank's basic global ANS components in 2005, our year of calculation for data reasons to be given in Section 4.3. Aggregation over countries uses market exchange rates (with no equity weightings), but using purchasing-power-parity exchange rates makes little difference. The World Bank reports ANS as a percentage of global gross national income, which differs from global GDP, our measure of output, by only minor statistical errors. The 9.3% ANS result in Table 1 is little publicized, but it suggests no general concern for future global well-being, despite the overall ANS decline since 1975 shown in Fig. 1.

The omissions here of population growth and technical progress are addressed below in Section 4.3. Practical difficulties in measuring many components in Table 1 are discussed by the World Bank (2011: 21-23); the Bank's results are frequently revised; and some important global environmental threats like biodiversity loss and nitrogen pollution are extremely hard to value and therefore omitted.

Table 1. World Bank (2013) global Adjusted Net Saving (ANS) components in 2005

Components, $\{P_1\dot{K}_1,...,P_j\dot{K}_j\}$	Size (as % of global GDP)
Net saving (gross saving, assumed to be invested in manufactured capital, minus depreciation of that capital)	8.7%
Public education spending (a proxy for investment in human capital)	4.3%
Market valuations of:	
Depletion of fossil-fuel energy	–2.9%
Depletions of 10 minerals including phosphate	–0.2%
Net forest depletion	–0.0%
Non-market valuations of:	
Human health damages from particulates emissions	–0.2%
Discounted long-term economic losses from climate change caused by current anthropogenic CO_2 emissions	–0.4%
Total basic ANS $(\mathbf{P}.\dot{\mathbf{K}})$	9.3%

3.3. Another approach

Another approach to empirical sustainability measurement has been developed from theory originated by Dasgupta and Mäler (2000), with notable recent contributions being Arrow et al. (2012) and UNU-IHDP and UNEP (2012). This approach appears to measure sustainability in non-optimal economies, and thus to avoid our problem of using a sustainability theory that applies only to optimal economies. But it actually offers no advantage for our purposes, because it generally defines an economy's sustainability at *t* quite differently, as *instantaneously* non-declining welfare ($\dot{W}(t) \geq 0$ at *t*).[8] The approach then shows how $\dot{W}(t) \geq 0$ at *t* can translate in non-optimal economies into comprehensive wealth, measured at constant real prices, being non-declining at *t*; or into variants of ANS, called comprehensive investment in Arrow et al. and inclusive investment in UNU-IHDP, being non-

[8] The original definition of sustainable development in Dasgupta and Mäler (2000: 83), though, was non-instantaneous: "...from now, utility must never decline".

negative at *t*. So while many details of comprehensive investment calculations in the Dasgupta-based literature differ from the World Bank's ANS calculations − in particular, Arrow et al. found huge values for health capital, which we do not include here − the theoretical link that one can then make with sustainability as defined in (4) is no different. Both approaches also face the same problems of finding the shadow prices needed to estimate ANS (Smulders, 2012).

4. Our modifications to DICE and to ANS

4.1. Choosing the DICE-2007 model for modification

Fankhauser's (1994) method of valuing CO_2 emissions, as used in World Bank ANS, was designed for small-scale emission control projects, and cannot calculate SCCs under optimal or no emissions control, or corresponding values of technical progress. Our requirement in (4) for all these values led us to modify DICE-2007 (Nordhaus, 2008), one of the DICE/RICE series of IAMs including RICE-2010 (Nordhaus, 2010, where R = Regional), DICE-2010, and DICE-2013 (Nordhaus, 2013). Each model assumes global welfare maximization, with or without control of industrial CO_2 emissions, and includes exogenous technical progress. So each can yield all our required values, in contrast to literature-based CO_2 valuations (e.g., Tol, 2009), or to most other IAMs.[9] The relative simplicity and generally good documentation of DICE/RICE models further make them a suitable choice for our inductive method. DICE-2007 is the most suitable, since RICE contains regional detail irrelevant to our global analysis, and neither DICE-2010 nor DICE-2013 was fully documented at the time of submission.[10]

DICE-2007's SCC is close enough to cause no loss of accuracy when we use it in place of the World Bank's SCC in our estimates of ANS based on standard DICE.

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[9] WITCH (Bosetti et al., 2006 and subsequent papers) might be developed to yield the values needed for our approach, but far less readily than DICE.

[10] DICE-2013's latest (October 2013) damage function is very close to DICE-2007's.

Normalized to US2005$, SCC is $24.5/tC in World Bank (2011: 78); and $27.3/tC in 2005 in DICE-2007's optimal run (Nordhaus, 2008: 92), where optimality would require all policy-makers to create a uniform carbon price close to this SCC, using an emissions tax or trading scheme with 100% participation (i.e., covering all global emissions). SCC is $28.9/tC in 2010 in RICE-2010's optimal run, so using RICE would change little here. Reasons for not using recent, probabilistic variants of DICE were given in Section 2.2.

4.2. Modifying DICE inductively to revalue CO_2 emissions

For reasons already discussed, we derive a precautionary SCC inductively, by modifying DICE so it becomes economically optimal for the world to be likely to stay within an agreed warming limit. We choose the well-known 2 °C limit, and "likely" means "with about 70% probability" – near the bottom of the 66-90% range for "likely" used by IPCC (2007) – which allows us to use a result from probabilistic climate science to calibrate our deterministic method. Like most IAM literature, we omit a detailed description of DICE, which is documented in Nordhaus (2008), with its computer code available in Nordhaus (2013). For reasons given earlier, we use DICE's "descriptive", market values for discount rate parameters rather than any "prescriptive", ethical values as in Stern (2007). We make a likely, 2 °C warming limit optimal by changing three DICE elements: the climate damage function, $\omega(T)$; the path of non-CO_2 radiative forcing over time t, labeled $F_{EX}(t)$; and the climate (temperature) sensitivity parameter, labeled χ; see Appendix C for the code used.

The relationship among these three changes needs explanation. First, we do not just impose an exogenous 2 °C warming constraint as in Nordhaus (2008), because 2 °C is too low to be optimal if DICE's modest damage function in (2) is valid. Next, we judge it insufficiently precautionary to modify only DICE's damage function, because of results in column (b) of Table 2. There we assume a temperature exponent N = 5 (the highest value considered by Ackerman et al., 2010, though Dietz and Asheim, 2012 considered N = 7) to give a damage curve with a steep threshold that embodies a precautionary approach to tipping elements in the climate system (Lenton et al., 2008; Richardson et al., 2011). We then find by induction that a = 0.00072 would make 2 °C maximum warming optimal, but would result in 1400 $GtCO_2$ cumulative CO_2 emissions during 2000-50. In a much-cited climate model (Meinshausen et al., 2009), such emissions are equivalent to only a ~55% chance of achieving a 2 °C maximum under uncertainty, which we consider not "likely" enough for risk-averse policy-makers.

Table 2. Our modifications to standard DICE assumptions and results

		(a) Standard DICE	(b) DICE with steeper damage as the only change in parameters	(c) Our base-case modified DICE
Model parameters:				
Parameters in climate damage function (proportion of global GDP lost), $\omega(T) = aT^N / (1+ aT^N)$ (1)	N	2	5	5
	a	0.0028388	0.00072†	0.00082†
Non-CO_2 net radiative forcing, $F_{EX}(t)$ (t = (year–2005)/10)		0.36 × [min(t/10,1)] – 0.06 (Wm^{-2})	0.36 × [min(t/10,1)] – 0.06 (Wm^{-2})	0.25 × [min(t/10,1)] × CO_2 forcing
Climate sensitivity, χ (°C)		3	3	4
Model results:				
Maximum global warming T if CO_2 emissions are optimal (°C)		3.5	2.0†	2.0†
Cumulative, optimally controlled CO_2 emissions, 2000-50 ($GtCO_2$)		1670	1400	1110
† In our modifications, maximum, global warming is an exogenous assumption, and parameter a is induced so that this maximum is economically optimal.				

We therefore make two extra changes, each supported by recent climate science, to lower the cumulative emissions that our modified DICE calculates as being compatible with any given maximum warming. We thus arrive at a precautionary recalibration of DICE, with a deterministic form of higher risk aversion (by achieving the equivalent of a ~70% chance of 2 °C maximum warming), as well as a higher climate damage function.

One extra change is to non-CO_2 net radiative forcing. DICE's $F_{EX}(t)$, which is not separately documented in Nordhaus (2007), is independent of the CO_2 emissions path and results in non-CO_2 forcing peaking at only 6-7% of CO_2 forcing in 2105. By contrast, IPCC (2007, Table 5.1) estimated that at stabilization, CO_2-equivalent concentrations (including non-CO_2 gases), closely reflecting overall radiative forcing, would over a wide range be at least 25% above CO_2-only concentrations. Our base-case modified DICE, defined by column (c) of Table 2, matches this by assuming $F_{EX}(t)$ starts at zero in 2005, as in IPCC (2007), and rises to 25% of CO_2 forcing in 2105 and thereafter. Higher, uncontrolled CO_2 concentrations will thus be associated with higher non-CO_2 forcing, rather than unchanged non-CO_2 forcing as less plausibly assumed in DICE. Our non-CO_2 forcing turns out to be higher overall in the optimally controlled case as well (Fig. 3).

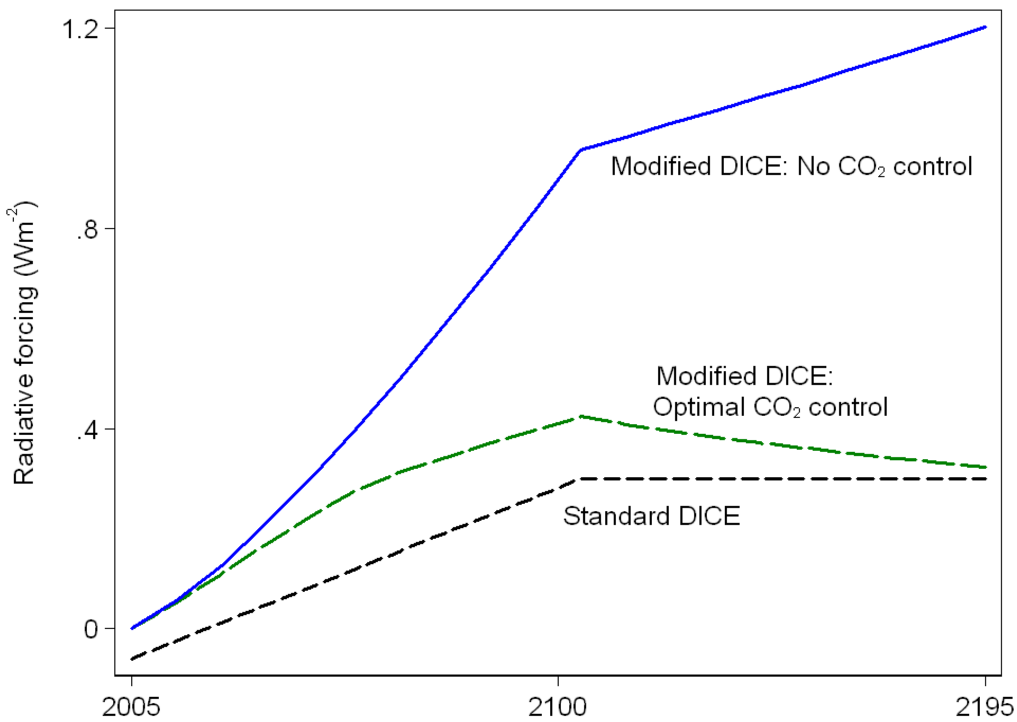

Fig. 3. Non-CO_2 net radiative forcing in standard DICE and our modified DICE

Our last change is to raise climate sensitivity χ from 3 to 4 ^oC, which Sherwood et al. (2014: 40) concluded is the "most likely" value. We then find by induction, still assuming $N = 5$, that our changes to $F_{EX}(t)$ and χ together change the damage function to $\omega(T) = .00082T^5 / (1+.00082T^5)$ and lower the 2000-50 emissions consistent with 2 ^oC maximum warming down to ~1100 $GtCO_2$, as shown in column (c). Such cumulative emissions raise the chance in Meinshausen et al. of achieving a 2 ^oC limit to ~70%, as required. In keeping with our interpretation that the 2 ^oC (or any similar) warming limit primarily reflects a policy of protecting future generations from climate damage, rather than encouraging higher general intergenerational concern, this function is much higher than DICE's and other notable recent damage functions (Fig. 4), and shows a strong threshold effect over a 3−5 ^oC warming range.

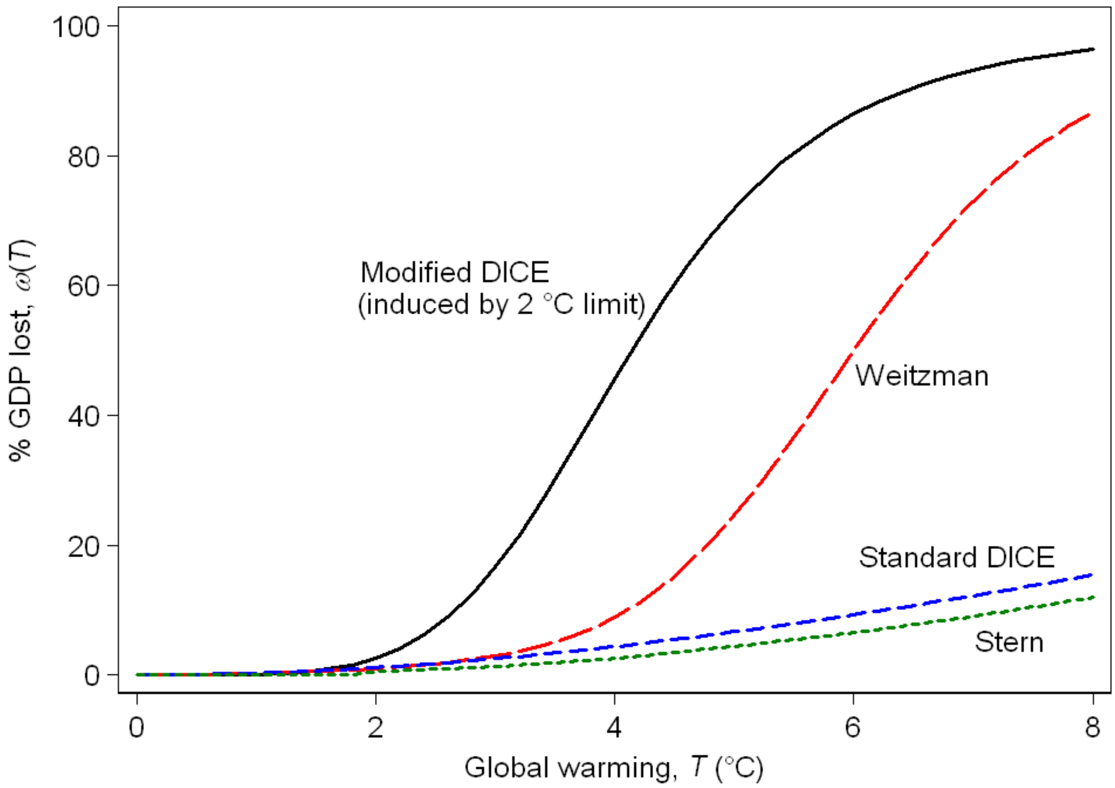

Fig. 4. Global warming damage functions, $\omega(T)$. Our modified DICE function is compared to those of Weitzman (2012), standard DICE (Nordhaus, 2007), and Stern (2007).

4.3. Adjustments to ANS for population growth and exogenous technical progress

We estimate that $n\mathbf{P}.\mathbf{K}$, the population deduction in (4), was 4.6% of global GDP in 2005, as follows:

Growth rate of global population in 2005, n = 1.19 %/yr (World Bank, 2013).

Tangible wealth per person, $\mathbf{P}(2005).\mathbf{K}(2005)/L(2005)$ = 27.12 k$/person (World Bank, 2011: 181)

GDP per person in 2005 = 7.06 k$/person.yr (World Bank, 2013)

1.19% x 27.12 / 7.06 = 4.6%.

For reasons of data availability, the World Bank's estimates of tangible wealth, $\mathbf{P}(t).\mathbf{K}(t)$, are based on a different set of stocks, **K,** than used for their basic ANS, $\mathbf{P}(t).\dot{\mathbf{K}}(t)$ (World Bank, 2011, Appendices D-E). Human capital and environmental resource stocks, respectively changed by cumulative education expenditures and cumulative emissions, are excluded from tangible wealth, both for data reasons, and with an environmental stock like CO_2 concentration because its effect per person is undiluted by population growth. Data on tangible wealth are available only for 1995, 2000, and 2005, which finally explains our choice of 2005 as our year of modified ANS calculations. As discussed in Section 3.1, any difference in non-CO_2 prices and quantities between paths with controlled and uncontrolled CO_2 emissions is ignored here, and deserves future research.

The lack of appropriate data on overall technical progress makes estimating its current discounted value, x in (4), infeasible for many individual countries, but we can estimate a global x from DICE's assumed growth in total factor productivity, as described in Appendix B**.** Since x depends on not just exogenously growing total factor productivity, but also endogenous changes to manufactured capital resulting from past investment and depreciation, we can and do compute different values for x on paths with controlled and uncontrolled emissions, unlike with the cost of population growth.

The number we finally add to ANS is not *Lx*/GDP, the percentage value of gross technical progress. World Bank ANS already includes public education spending (a rough estimate of total education spending), estimated at 4.3% of global GDP in 2005, as a reclassification of spending from consumption to investment in human capital (Table 1). Since human capital growth through education, a cause of total factor productivity growth (Solow, 1957), is not included in DICE's manufactured capital, it must be already included in DICE's productivity growth. Including both education spending and all *Lx*/GDP in ANS would therefore be double-counting, so the technical progress values reported below are for (*Lx*/GDP – 4.3%).

5. Results and sensitivity testing

5.1. Results

Because of its modest damage function, standard DICE's economic results and their application to ANS in Table 3 show very little difference between a future with optimal control of industrial CO_2 emissions, where maximum global warming is 3.5 ^{o}C, and a future with no control, where maximum warming is 6.1 ^{o}C. By contrast, emissions control matters hugely in our modified DICE model, because of our changes in Table 2 that make a likely, 2 ^{o}C warming limit optimal.

If industrial emissions are controlled to respect this limit, then our base-case results in Table 3 value the current ANS emissions deduction at 2% of global GDP, about 4 times higher than the World Bank's, but we also add 16% of GDP for future technical progress. Our modified ANS is then 19%, markedly more reassuring about the sustainability of current, global well-being than the World Bank's 9% in Table 1, mainly because of the included benefit of technical progress, which on an optimal path far outweighs the cost of population growth and our higher valuation of emissions. Consistent with this, average well-being in 2105 is projected to be only 4% below the standard DICE level (Fig. 5a), despite the extra cost of much faster CO_2 abatement.

Table 3. Global climatic and economic results using standard DICE and our modified DICE over 2105-2595. Cases (a) and (c) are as in Table 2, whose case (b) is irrelevant here.

			(a) Standard DICE	(c) Our base-case modified DICE
Optimal control of industrial CO_2 emissions	Maximum global warming (°C)		3.5	2.0
	Social cost of CO_2 emissions (SCC) in 2005	($/tC)	27	131
		(% GDP)	–0.5	–2.2
	#Value of technical progress, as at 2005 (% GDP)		15.7	16.0
	##Adjusted Net Saving (ANS) in 2005 (% GDP)		20.5	19.0
No control of industrial CO_2 emissions	Maximum global warming (°C)		6.1	6.0
	SCC in 2005	($/tC)	28	1455
		(% GDP)	–0.5	–24.4
	#Value of technical progress, as at 2005 (% GDP)		15.6	7.2
	##ANS in 2005 (% GDP)		20.3	–12.0
	Decade of peak well-being in DICE		None	2065

#Net of 4.3% educational spending (see end of Section 4).

##Sum of CO_2 emissions and technical progress as shown here, plus 5.2% GDP for sum of net saving (8.7%), public education spending (4.3%), natural resource depletion (–3.1%) and particulates pollution (–0.2%) from Table 1, and of population growth (–4.6%) from Section 4.3.

But with no CO_2 control, warming is much faster, so each ton of current emissions causes much more future damage. This raises our deduction for current emissions another 11-fold, from 2% to 24% of global GDP; and owing to depressed future investment (Appendix B, Fig. 5b), it also lowers the sustainability value of technical progress to only 7%. Our modified ANS in 2005 is then –12% of GDP (Table 3).

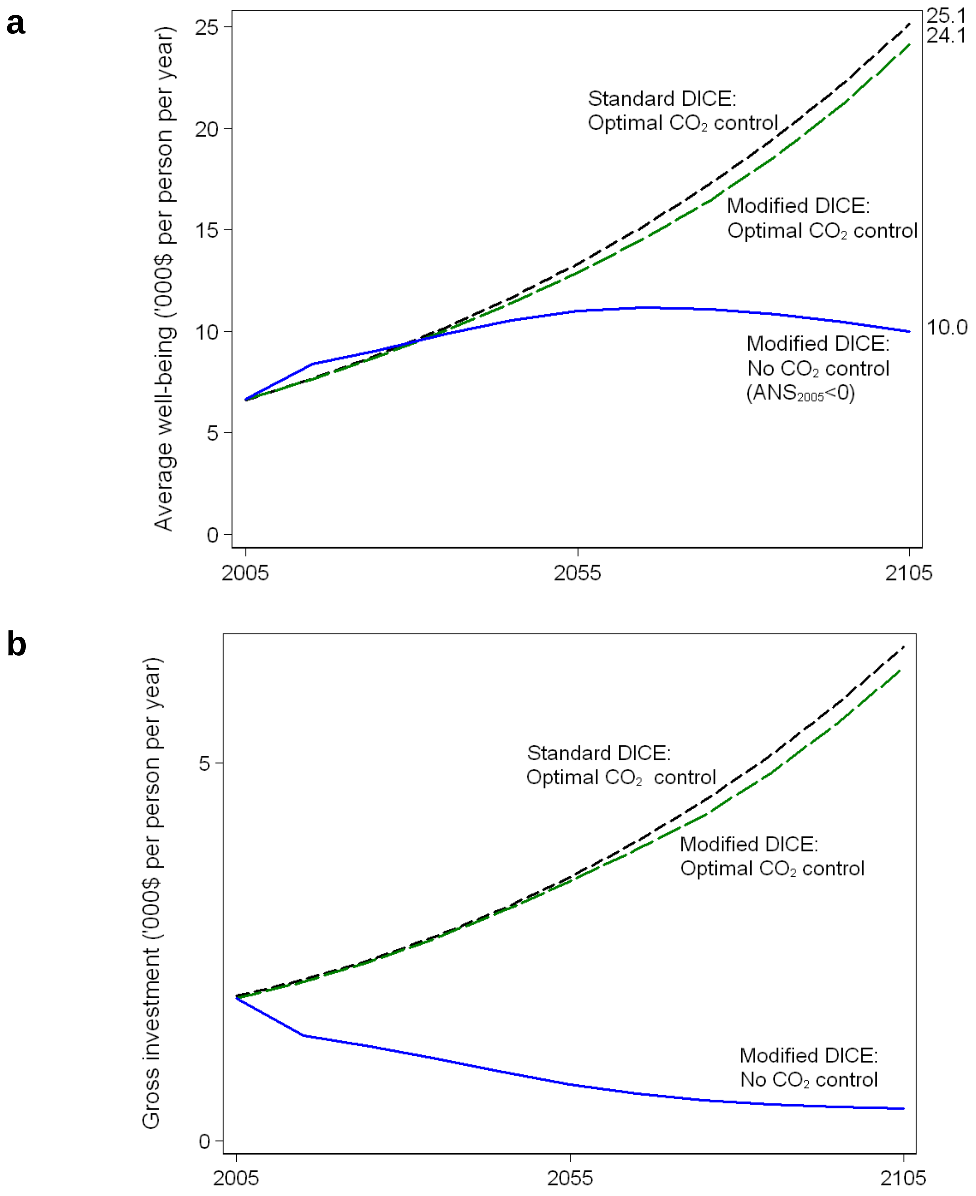

Fig. 5. Average well-being (a) and gross investment per person (b) in our base-case modified DICE, on different vertical scales. (Standard DICE graphs for No CO_2 control are omitted because on them, well-being and investment are only 0.7% and 1.4% below Optimal in 2105.)

Average human well-being is higher for the first two decades (Fig. 5a), but then grows more slowly and peaks in 2065, because climate damage eventually exceeds the benefits from capital investment and technical progress. Given the absence of any theory-based alternative, this suggests that negative ANS may serve as a heuristic indicator of the unsustainability of an uncontrolled, business-as-usual development path. So on the basis of just Table 3's results, our provisional answer to both our opening questions would be 'yes': with optimal environmental management, current well-being is found to be sustainable, even with a "strong" limit on global warming; but with uncontrolled environmental damage, the future rise in well-being is unsustainable. Together these results would challenge the beliefs of both environmental pessimists and environmental optimists, and we can but hope such challenges would inspire some more nuanced debate between supporters of the two paradigms. But given the many contentious assumptions on which our results rest, they first need to be tested, as follows.

5.2. Sensitivity testing

DICE contains 44 non-trivial parameters (Nordhaus, 2008: 58). Anderson et al. (2014) used Monte Carlo simulations to perform a probabilistic, global sensitivity analysis on DICE, whereby all its parameters are varied simultaneously, with each assigned a uniform distribution from 10% below to 10% above its base value, and with all base values given equal standing. In contrast to standard, one-factor-at-a-time analyses, this allows for interactions among parameters, and avoids prejudging which parameters are worth selecting for analysis. However, the unavoidable uncertainty about what parameters to include in an IAM in the first place remains (Dietz and Fankhauser, 2010). Also, using a uniform, non-judgmental approach to testing values for included parameters can discard some useful knowledge. For example, some base values for parameters can be calibrated quite well against current observations, and are thus more reliably known than others; and credible ranges of variability may be much wider for some parameters than for others. So while a global sensitivity analysis would undoubtedly be desirable, a good one is necessarily complex, and we leave these complexities to future research. Instead we have used our judgment to choose parameters that define the eight, one-factor-at-a-time tests shown in columns (d)-(k) of Table 4, which are ranked in descending order of impact on no-control ANS compared to our base case in column (c).

Table 4. Sensitivity tests of our modified DICE model results. Case (c) is as in Table 2. Notes on technical progress and ANS results are as in Table 3.

			(c) Base case of our modified DICE	(d) Higher warming limit: 2.2 not 2.0 °C	(e) Lower climate sensitivity: χ = 3.6 not 4 °C	(f) Higher capital elasticity of output: γ = 0.33 not 0.3	(g) Total factor product'y *A* always 10% lower	(h) Lower damage exponent: *N* = 4.5 not 5	(i) Lower participation rate: 90% not 100%	(j) Lower consumption elasticity: α = 1.8 not 2	(k) Faster technical progress: GA0 = 0.101 not 0.092
Optimal control of industrial CO_2 emissions	Social cost of CO_2 emissions (SCC) in 2005	($/tC)	131	97	108	105	121	136	160	134	127
		(% GDP)	–2.2	–1.6	–1.8	–1.8	–2.0	–2.3	–2.7	–2.2	–2.1
	Value of technical progress, as at 2005 (% GDP)		16.0	15.9	15.9	15.4	18.7	16.0	16.0	17.1	20.0
	Adjusted Net Saving (ANS) in 2005	(% GDP)	19.0	19.4	19.3	18.8	21.9	18.9	18.4	20.0	23.1
		Rank re (c)*	–	5	6	7	2	8	4	3	1
No control of industrial CO_2 emissions	SCC in 2005	($/tC)	1455	801	901	929	1053	976	1872	1310	1460
		(% GDP)	–24.4	–13.4	–15.1	–15.6	–17.7	–16.4	–31.4	–22.0	–24.5
	Value of technical progress, as at 2005 (% GDP)		7.2	8.6	8.3	8.0	9.8	8.2	6.6	7.7	10.1
	ANS in 2005	(% GDP)	–12.0	0.4	–1.6	–2.4	–2.7	–2.9	–19.6	–9.1	–9.2
		Rank re (c)*	–	1	2	3	4	5	6	7	8
	Decade of peak well-being in modified DICE		2065	2075	2075	2075	2075	2075	2065	2075	2065

* Ranked in descending order of % GDP change from base-case ANS in (c) (so No-control ANS is least sensitive to a 10% change in parameter (k), ranked 8).

Our choice was nevertheless mainly inspired by Anderson et al.'s method and results. First, each of our eight parameters is changed by 10% from its base value in our modified DICE, with the changes all chosen to improve no-control ANS, except for the emissions-pricing participation rate (column (i)), which cannot be improved from its initial level of 100%. Second, the five parameters which define columns (e)-(h) and (j) are those with the most impact on optimal SCC in Anderson et al.'s analysis (excluding *a* in Table 2, which we always determine inductively so that the warming limit is still optimal). Two further parameters − the warming limit in (d), and the rate of technical progress in (k) − were of obvious interest, given their role in our ANS methodology. Our eighth parameter was the participation rate. We found ANS to be quite sensitive to this, even though it was one of the least sensitive parameters in Anderson et al.'s analysis, which started from DICE's standard values for the damage parameters *N* and *a*. Moreover, a halved participation rate seems much more likely and thus worth considering than, say, a doubled total factor productivity, which again shows the limits of a strictly non-judgmental approach to sensitivity analysis.

Our tests all show large differences between optimal and no-control SCCs, and between optimal and no-control ANSs. This is reassuring for our methodology, if unsurprising given how much higher climate damage is in our modified DICE than in conventional models. The smallest difference between optimal and no-control ANSs is 19 percentage points, in (d) where the warming limit is 2.2 °C. This higher limit nearly halves the no-control SCC and causes the greatest change in no-control ANS from our base case (c), making it just positive. However, Table 4's last row shows that in (d), peak well-being in modified DICE is delayed by only a decade, rather than avoided, suggesting only a one-sided link between ANS and sustainability also in the no-control case.

Despite no-control ANS being most sensitive in our tests to two climate-related parameters (the warming limit in (d), followed by climate sensitivity in (e)), two economic parameters (capital elasticity in (f) and total factor productivity in (g)) are close behind, suggesting no particularly sharp focus on which parameters deserve top priority in future research. Moreover, sensitivity depends on the policy question considered to be of interest. The rank order of sensitivity of ANS is very different between optimal control and no control, with some changes in ANS from base case (c) even having opposite sign for optimal and no-control runs, as with cases (f) and (h). The rank order of sensitivity is different again if SCC (CO_2 control) rather than ANS (global sustainability) is of interest. For example, a 10% change in the rate of technical progress, (k), has the least effect on no-control ANS and the second-least effect on controlled SCC, but the greatest effect on controlled ANS.

6. Can ANS use induction to include other global environmental concerns?

Here we consider if ANS might be further extended to include other major environmental concerns for global sustainability, such as Rockstrom et al.'s (2009) "planetary boundaries". A full treatment would need another paper, and references here are merely illustrative. Nevertheless, considering biodiversity loss, and conversion of atmospheric nitrogen to reactive forms – judged by Rockstrom et al. to be the two most exceeded planetary boundaries – together with food security, suggests some potential for our inductive approach to make ANS yet more inclusive, but also the great difficulties of doing so. More straightforward, non-inductive extensions would also be possible, such as including intragenerational inequality via regional disaggregation (e.g., after Nordhaus, 2010), endogenous technical change (e.g., after Popp, 2004), or carbon-cycle feedback (as suggested by Hof et al., 2012).

Inclusion of any new environmental variable *i* in ANS requires an estimate of both its current net stock change, $\dot{K}_i$, and its current, discounted social value per unit, P_i. Such estimates for global biodiversity loss are conceivable by developing a loss model like that in Braat and ten Brink (2008), which uses population, GDP, energy use, and food production as drivers. A precautionary value might then be induced from an exogenous, "strong sustainability" limit on biodiversity loss, similar to our induction of a precautionary CO_2 value. But unlike CO_2 emissions, biodiversity is heterogeneous, with Braat and ten Brink's use of mean species abundance as its aggregate measure contrasting with Rockstrom et al.'s use of total species number. As for atmospheric nitrogen conversion, this flow is measurable, but as yet there is no global modeling of its determinants. So including nitrogen in ANS, even inductively, is even further off.

Growing concern is also being expressed (e.g., by Godfray et al., 2010) about the world's future ability to feed its population, and hence about sustainability as defined here, since food is vital to well-being. But by contrast with biodiversity loss and nitrogen pollution, food production and consumption are mainly marketed, hence already represented, albeit imperfectly, in our modified ANS. For example, the World Bank (2011) estimates of $n\mathbf{P}.\mathbf{K}$ in (4) include market values for four categories of rural and urban land (say $P_1K_1,...,P_4K_4$), and thus how population growth cuts food supply per person *ceteris paribus* by cutting available land per person. However, net changes in quality-adjusted land stocks, $(\dot{K}_1,...,\dot{K}_4)$, are not available separately (World Bank, 2011: 38) and so are excluded. By contrast, phosphate rock is included in ANS's mineral depletion term (Table 1), so its valuation there at much less than 0.2% of global GDP lends no support to Cordell et al.'s (2009) grave concern about the effect of future phosphorus depletion on global food security. Supporting this concern within a modified ANS would require a calculation, perhaps using an extended IAM, that the ultimate non-substitutability of phosphate fertilizer in food production implies a sustainability price (Pezzey and Toman, 2002) vastly bigger than the market-based rental price currently used in World Bank ANS.

7. Conclusions

More than two centuries after Malthus started the debate on the limits that finite environmental resources and population growth impose on the long-term, sustainable growth of human well-being, there is a persistent gulf between optimistic and pessimistic views on such limits and the indicators supporting them. Economic ("weak") indicators like the World Bank's Adjusted Net Savings (ANS) and physical ("strong") indicators like the Ecological Footprint suggest starkly different, respectively optimistic and pessimistic, futures for the world, and in particular attach vastly different importance to current CO_2 emissions. The Earth's uniqueness, and the complexity and long time-scales of key global changes, mean that many limits of substituting human-made for environmental inputs to well-being are, and will stay, highly unknowable. Opposing views on global sustainability will thus tend to remain beliefs or paradigms, whose disagreement cannot be resolved by normal scientific methods.

To address this gulf and help inform policy-making on global sustainability issues, we have constructed an experimental, more inclusive, hybrid ("weak/strong") indicator of global sustainability. We extended World Bank ANS to include two important omitted features – the cost of exogenous population growth and benefit of exogenous technical progress – and replaced the CO_2 emissions valuation by either one of two, much higher, precautionary valuations, which assume either optimally controlled or uncontrolled future emissions. Because damage from future global warming is highly unknowable, we calculated these valuations inductively: we modified the damage, climate sensitivity, and non-CO_2 forcing assumptions in the deterministic, DICE integrated assessment model so that an emissions path likely to limit global warming to 2 ^oC (an agreed "strong sustainability" constraint which *is* known) becomes economically optimal. However, such induction does not make the cost of exceeding 2 ^oC warming infinite, as logically implied by the language of (absolute) non-substitutability used in much "strong sustainability" writing. And to focus on climate damage rather than general intergenerational concern as the main driver of climate policy, we left discount rates unchanged at market-based, policy-relevant values.

If future CO_2 emissions are optimally controlled, our base-case, modified ANS is substantially higher than World Bank ANS, mainly thanks to including the benefit of exogenous technical progress. Consistent with this, our modified-DICE model has well-being growth very close to DICE's original. But if emissions are uncontrolled, our CO_2 cost is much higher than the World Bank's, (exogenous) technical progress is less beneficial because (endogenous) future investment falls, and base-case ANS is negative. Consistent with this, well-being in modified-DICE peaks in 2065, contradicting the conventional economic expectation of limitless growth. This suggests that a negative "uncontrolled ANS" – one using valuations based on a future path of uncontrolled environmental damage – may be a useful, if heuristic, indicator of the unsustainability of rising well-being on that path. Our results are sensitive to changes in parameter values, but none of eight key parameters tested was much more important than the others, though the warming limit used for induction, still deserves special scrutiny. Also, which parameters are considered the most important depends on the policy context of interest (climate policy or global sustainability, controlled or uncontrolled scenarios).

Our highly provisional answers to our two opening questions would thus be that the current level of well-being may be sustainable if the global economy and environment are optimally controlled in future; but rising well-being may not be sustained for another century or so if business-as-usual trends of largely uncontrolled environmental depletion continue. Such results depend on unavoidably contentious assumptions, and we regard our contribution here as being perhaps more our methodology than our base-case results. However, our results do show how carefully qualified optimistic and pessimistic views on global sustainability can both be right. How well the global environment will in fact be controlled is a separate issue, though, on which optimistic or pessimistic views may be held independently.

Several topics remain for future research. An important but tough challenge would be to use induction to include "planetary boundaries" for other global environmental threats in ANS, like biodiversity loss and nitrogen pollution, which are also unknowable enough to be near-impossible to value directly. An easier extension in terms of data-gathering, but perhaps harder computationally, would be to use induction in existing, probabilistic versions of DICE which explicitly model important aspects of uncertainty (as opposed to unknowability) that our deterministic approach omits, like policy-makers' risk aversion. Adding carbon-cycle feedback, endogenous population change, and endogenous technical progress would also be desirable. The ultimate aim might be to extend such a model even further to include important sectors like energy and minerals depletion, so the model could then be used to make direct predictions of global sustainability, not just provide values for a hybrid ANS as here. However, a separate, more complete model might actually have less influence on policy than a further modification of World Bank ANS. The theoretical, data-gathering, and modeling challenges of all such extensions are severe, so multiple, simpler sustainability indicators will still be needed. But we hope our attempt to build a single, more inclusive, economic indicator of global sustainability which incorporates both technical progress and a physical, environmental constraint will be of interest to policy-makers, and a useful addition to the mostly polarized debate between environmental optimists and pessimists.

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Appendix A. Further details of ANS theory

Pezzey's (2004) theoretical link between extended ANS and sustainability in (4) is summarized as follows. Society's intertemporal welfare $W(0)$ is the discounted present value of average utility (well-being) per person weighted by population:

$$W(0) := \int_0^\infty L(t)\, u[\mathbf{C}(t)/L(t)]\, e^{-\rho t} dt\,, \tag{A.1}$$

and four key restrictive conditions for the link in (4) to hold are:

- $\mathbf{C}(t)$ is "extended consumption", the vector of all attributes, including consumption of goods and services and various measures of environmental quality, whose per-person levels determine a representative agent's instantaneous utility, $u(\mathbf{C}/L)$;
- $L(t) = L_0\, e^{nt}$ is population, assumed to be growing exogenously at constant rate n;
- $\rho > 0$, the utility (pure time) discount rate is constant; and

• $W(0)$ is maximized subject to $[\mathbf{C}(t), \dot{\mathbf{K}}(t)] \in S[\mathbf{K}(t), L(t), t]$ at all times, where $S[.]$, the economy's "extended production" possibility set, has constant returns to scale, and is non-autonomous (depends directly on time t) to allow for exogenous technical progress.

Term $x(t)$ in (4), the per-person realized value of exogenous technical progress in expanding production possibilities over time, is:

$$x(t) := \int_t^\infty [\partial y(s)/\partial s] \exp\{-\int_t^s [r(z)-n]dz\}\, ds\,, \tag{A.2}$$

where $y(t)$ is (green) Net National Product per person and $r(t)$ is the real interest rate at time t (see Propositions 5 and 8 in Pezzey, 2004, which generalize and extend Weitzman, 1997). Appendix B explains how we estimate $x(t)$ empirically.

In addition to, or derived from, the four key conditions already noted, further assumptions needed to make (4) true include that:

(i) all decision-makers have perfect information over an infinite time horizon, and social planners use this to make the economy follow its optimal path over time;

(ii) the optimal time-path of utility is unique and non-constant;

(iii) all stocks affecting production and utility, **K**, and net investments in them, $\dot{\mathbf{K}}$, are measurable;

(iv) all such stocks have finite prices, **P**, which in turn assumes smooth substitutability everywhere between human-made inputs and natural inputs to production and utility;

(v) by measuring the welfare of just a representative agent, and discounting it over all time, all decision-makers are ethically willing to aggregate dollar values over all present and future people, and ignore all intranational, international, and intergenerational inequalities in well-being;

(vi) there are no public goods or bads (since the effect of these on utility would not be divided by population L as in (A.1), as noted in Pezzey 2004: 625); and

(vii) there are no renewable resource stocks with non-constant returns to scale.

Appendix B. Using DICE to estimate the ANS addition for technical progress

We estimate the per-person value $x(0)$ of exogenous technical progress using this discrete approximation of (A.2) applied to results from DICE runs:

$$x(t) \approx \sum_{s=t}^{18} [\Delta\tilde{y}(s)/\Delta s] \exp\{-\sum_{z=t}^{s} 10[r(z)-n(z)]dz\}ds, \qquad \text{(B.1)}$$

with t in decades as in DICE, but with r and n as annual rates, hence the required factor of 10. This approximates y, green Net National Product per person, as $\tilde{y}$, per-person output, net of climate damage ω and manufactured capital depreciation δK:

$$\tilde{y}(s) := \{A(s)[K(s)]^{\gamma}[L(s)]^{1-\gamma}[1-\omega(T)] - \delta K(s)\} / L(s) \qquad \text{(B.2)}$$

where previously undefined terms in DICE are two variables: (exogenous) total factor productivity $A(t)$, and (endogenous) manufactured capital $K(t)$; and two parameters: γ, the capital elasticity of Cobb-Douglas gross output, and δ, the rate of capital depreciation.

To compute $\Delta\tilde{y}(s)/\Delta s$ in (B.1), we start by computing annual growth rates of population and technology for $t = 0, ...,18$ (i.e. from 2005-2185) as

$$n(t) = [L(t+1)/L(t)]^{1/10} - 1 \quad \text{and} \quad g_A(t) := [A(t+1)/A(t)]^{1/10} - 1, \quad \text{respectively,} \qquad \text{(B.3)}$$

so the growth rate in $\tilde{y}(t)$ due solely to technical progress is

$$[\Delta\tilde{y}(t)/\Delta t]/\tilde{y}(t) = g_A(t) - n(t), \quad \text{and} \quad \Delta\tilde{y}(s)/\Delta s \quad \text{in (B.1) is} \quad [g_A(s) - n(s)]\tilde{y}(s). \qquad \text{(B.4)}$$

Next, we compute the geometric, annual rate of interest

$$r(z) := [1+r_{10}(z)]^{1/10} - 1, \qquad \text{(B.5)}$$

where $r_{10}(z)$ is the decadal interest rate computed by DICE.

We finally estimate $x(0)$ from (B.1). This is much lower on the no-control path than on the optimal path, because with no control, in anticipation of much higher climate damage, investment falls rather than rises over time (Fig. 5b). This leads to falling rather than rising capital, hence higher interest rates r and heavier discounting in (B.1).

Appendix C. Our modifications to DICE's computer code

Original lines of GAMS code for DICE-2007:

```
T2XCO2          Equilibrium temp impact of CO2 doubling oC  / 3      /
FEX0            Estimate of 2000 forcings of non-CO2 GHG    / -.06   /
FEX1            Estimate of 2100 forcings of non-CO2 GHG    / 0.30   /
A2              Damage quadratic term                       / 0.0028388 /
A3              Damage exponent                             / 2.00      /
FORCOTH(T) = FEX0 + .1*(FEX1-FEX0)*(ORD(T)-1)$(ORD(T)LT12) +
        0.36$(ORD(T)GE12);
FORC(T) =E= FCO22X*((log((Matav(T)+.000001)/596.4)/log(2))) + FORCOTH(T);
*s.fx("1") = .22;
```

[The last line is from Nordhaus's code, with * meaning that fixing the first-period saving rate s at 22% should be suppressed. However, experimentation shows that to get the exact results shown in Nordhaus (2008), the command s.fx("1")=.22; must not be suppressed, so we make it operational in our modified DICE, as shown below.]

Replacement lines in our modified DICE (Table 2, column (c)):

```
T2XCO2          Equilibrium temp impact of CO2 doubling oC  / 4      /
A2              Damage quadratic term                       / 0.00082 /
A3              Damage exponent                             / 5.00      /
FORCOTHM(T) = 0.025*(ORD(T)-1)$(ORD(T)LT12) + 0.25$(ORD(T)GE12);
FORC(T) =E= FCO22X*((log((Matav(T)+.000001)/596.4)/log(2))) *
        FORCOTHM(T);
s.fx("1") = .22;
```

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