Ecological Economics 116 (2015) 354–361

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Natural capital in integrated assessment models of climate change

Stian B. Hackett *, Erling Moxnes

System Dynamics Group, Department of Geography, University of Bergen, Fosswinckelsgt.6, N-5007 Bergen, Norway

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form 11 April 2015
Accepted 12 May 2015
Available online 11 June 2015

Keywords:
Integrated assessment models
Climate change
Natural capital
Optimal growth
Sustainability
Discounting

ABSTRACT

In integrated assessment models (IAMs) economic activity leads to global warming, which causes future economic costs. However, typical IAMs do not explicitly represent the role of natural capital. In this paper, the DICE model by Nordhaus (2008) is expanded with a natural capital variable that is affected both by climate change and by depletive effects of economic activity. Due to a synergy between the two effects, the optimal policy of the expanded model features more and earlier abatement of CO_2 emissions than DICE. Interestingly, the policy implications are different from what follows if one tries to capture the depletive effects on natural capital by simply reducing factor productivity growth in DICE. Acknowledging considerable uncertainty, simulations show that climate- and savings rate policies from the expanded model are more robust in the long term than policies that do not consider non-climatic depletion effects on natural capital.

1. Introduction

In the climate policy debate, there is disagreement about the extent to which one should reduce CO_2 emissions now to limit the future costs of global warming, or emphasize economic growth and let presumably wealthier future generations deal with the climate problem. How much weight one should put on each of these two recommendations depends largely on expectations about future wealth, and on the intragenerational distribution of costs and benefits. This paper focuses on the importance of natural capital for future wealth, but does not deal explicitly with the question of distribution.

Influential integrated assessment models (IAMs) focus on global warming as a byproduct of economic activity, e.g. PAGE2002 (Hope, 2006), which was used in the *Stern Review* (Stern, 2006) and DICE-2007 (Nordhaus, 2008). In these models, global warming causes costs (climate damage) to the future economy, expressed as a percentage reduction in global output given by an aggregate damage function. Some of these costs reflect negative climatic effects on natural capital such as ecosystems, freshwater, marine populations and other resources. Hence, IAMs incorporate climatic effects on natural capital as a part of the economic damage from climate change. However, typical IAMs do not represent how economic activity also can have depletive or degrading non-climatic effects on natural capital, for example by unsustainable resource use and toxic pollution. The degradation of natural capital through non-climatic effects is another major byproduct of economic activity — see for example Hamilton and Clemens (1999), Arrow et al. (2004), and the Milllennium Ecosystem Assessment (2005). For an introduction to the concept of natural capital, see Costanza and Daly (1992).

Most likely, there are cost synergies of losing natural capital from climatic and non-climatic factors. Plausible examples of economic sectors at risk from both climate change and non-climatic degradation effects include agriculture, forestry, water-intensive sectors, and marine sectors. Regardless of causes, the potential economic costs of losing natural capital are large, especially if we also consider the value of nonmarket natural services — see for example Costanza et al. (1997) and Sukhdev (2009).

This raises three important questions for IAMs. First, what are the consequences of non-climatic degradation effects on natural capital for long-term economic growth, consumption, and CO_2 emissions? Second, will future climatic effects on natural capital be more damaging if natural capital is already degraded by non-climatic effects? Third, how would a more explicit representation of non-climatic effects affect optimal climate policies in a cost-benefit analysis?

This paper explores these questions by incorporating a representation of natural capital in DICE-2007 (Nordhaus, 2008) — hereafter "DICE". In the extended model, called "DICE-NC", we make a distinction between "climatic effects" and "non-climatic effects" to distinguish two ways that natural capital can be degraded by economic activity. Climatic effects on natural capital are assumed to constitute a fraction of the economic damage from climate change already calculated in DICE. Non-climatic effects are modeled as an additional, separate byproduct of economic activity. Moreover, like CO_2 emissions, non-climatic effects accumulate. The total accumulated degradation of natural capital from climatic and non-climatic effects causes costs to the economy through a cost function similar to the one used for climate only in DICE. When the two effects are added and the cost increases convexly with total

* Corresponding author.
E-mail addresses: stianhackett@gmail.com (S.B. Hackett), Erling.Moxnes@uib.no (E. Moxnes).

http://dx.doi.org/10.1016/j.ecolecon.2015.05.009
0921-8009/

degradation, the total cost is higher than what it would be for two separate effects. Results show that under these assumptions, the optimal solution of DICE-NC features more and earlier abatement of CO_2 emissions than the reference DICE solution. It is also shown that the explicit representation of non-climatic effects in DICE-NC has different policy implications from what follows from simply reducing factor productivity in DICE.

Several interesting studies have addressed limitations in how IAMs treat climate effects on natural capital or the environment (Tol, 1994; Neumayer, 1999, 2007; Hoel and Sterner, 2007; Sterner and Persson, 2008; Heal, 2009). These studies mainly address how IAMs may imply too optimistic assumptions about substitutability between market consumption goods and environmental goods in the utility function. Our approach differs in that we model natural capital degradation from non-climatic effects like degradation from climatic effects is modeled in DICE; as endogenously generated costs that affect the market economy and the path of economic growth.

Other methodological problems with IAMs or cost-benefit analysis applied to climate change – see for example van den Bergh (2004), Pindyck (2013), and Moxnes (2014) – are not dealt with in the paper. The limited purpose of the study is to show how explicit modeling of natural capital influences policy recommendations within the standard cost-benefit framework.

The paper is organized as follows: Section 2 describes the framework for analysis used in DICE. Section 3 describes how DICE-NC differs from DICE. Section 4 presents optimization results and compares the policies of DICE-NC and DICE. Section 5 analyzes the role of uncertainty when formulating policy without perfect knowledge about what the correct model is. Section 6 features a discussion and Section 7 concludes.

2. Background: Climate Change and Optimal Growth

DICE (Nordhaus, 2008) is a global model that builds on the optimal growth framework by Frank Ramsey (1928). Since its first incarnations in the early 1990s, the DICE model has been one of the most influential IAMs in the cost-benefit analysis of climate change and policy. Because of its transparency and influence, it is a useful starting point for the analysis in this paper. DICE extends the Ramsey framework with components that represent the carbon cycle, the climate, and economic damages from climate change. The modeled economy produces, consumes, and derives welfare from a single representative good, which allows DICE to frame the climate problem as an investment tradeoff. On the one hand, the world should abate its CO_2 emissions,[1] because global warming will reduce the consumption of future generations. On the other hand, the costs of abating emissions are immediate reductions in consumption, investment, and economic growth. Hence, abatement policies also lower future consumption.[2] The title of Nordhaus' book *A Question of Balance* (Nordhaus, 2008) reflects this dilemma.

DICE features an important distinction between gross and net output. Net output equals the gross output after subtracting the economic costs of global warming and the costs of abating CO_2 emissions. Net output is then allocated between consumption and capital investment. Indicated (unabated) fossil CO_2 emissions are a function of gross output. Hence, gross output is the model's driver of energy demand and the implied physical "effort" in the economy.[3]

DICE optimizes two policy variables over time to maximize discounted welfare: the emission control rate, which is the fraction of indicated CO_2 emissions that is abated, and the savings rate, which is the fraction of net output that is invested in new capital. If the costs of climate change and the costs of emission abatement also consist of capital investment, these investments are not included in the model's capital investment variable.

The reference run of DICE (Nordhaus, 2008) features less optimal abatement of CO_2 emissions than what is recommended by for example the *Stern Review* (Stern, 2006). Fossil CO_2 emissions are not fully abated until 2205, and the global average surface temperature peaks at about the same time, at 3.47 °C above the temperature around 1900.

3. The DICE-NC Model

The difference between DICE and the expanded model DICE-NC can be explained in systems terms. Fig. 1 shows how economic growth in DICE is driven by a positive feedback loop (*P1*) between the *capital stock* and *capital investment,* as well as exogenous growth in *population* and *total factor productivity*. A negative feedback loop (*N1*), which counteracts the drivers of growth, is formed by a link from *gross output* to *net output* via the *average atmospheric temperature*. This is a "natural capital feedback effect" that separates DICE from standard economic growth models.

DICE-NC expands DICE with another natural capital feedback effect, which represents the economy's impact on natural capital, shown by the dashed lines in Fig. 1. First, the effect of average atmospheric temperature on net output in DICE (the damage function) is split in two: a modified direct effect called *other climate damage*, and another via *climatic effects on natural capital*. Natural capital represents biotic and abiotic resource stocks and systems that are influenced by both climate and economic activity. Separating the two effects leads to the formation of the new negative feedback loop *N2*. *N1* and *N2* are modeled so that by themselves, their combined effect on the economy is equal to the original damage function in DICE. Hence, as long as the feedback loop *N3* is inactive, results remain identical to DICE. Second, *total degradation of natural capital* is the sum of climatic effects and *accumulated non-climatic effects on natural capital*. Non-climatic effects are caused by economic activity represented by gross output. This creates the negative feedback loop *N3* through the added dashed links from gross to net output. When this effect is activated, results will be different from DICE. In reality, some of the costs of natural capital degradation from non-climatic effects will take the form of capital investment and would show up as such in national accounts, just like some of the costs of emission abatement and climate change in DICE are likely to be investments. Like in DICE, these costs are not covered by the model's capital investment variable.

3.1. Equations

This section does not cover all the equations of DICE, only those that are needed to explain how the model has been changed. For a full overview of DICE, see Nordhaus (2008).[4]

3.1.1. Key Equations of the Original DICE Model

In DICE, Gross output $Y(t)$ is determined by a standard Cobb–Douglas production function:

$$Y(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{1}$$

[1] Other greenhouse gases, including CO_2 emissions from land use change, are exogenous in the model.

[2] There is also potentially a tradeoff associated with a limited stock of fossil energy that must be efficiently allocated over time, requiring some CO_2 abatement even in the absence of a climate policy. However, the optimal policy of DICE, which eventually reduces fossil-based emissions to zero, leaves most of the assumed recoverable fossil energy in the ground.

[3] In the model code, gross output is called *Gross world product gross of abatement and damages*, while net output is called *Gross world product net of abatement and damages* (DICE-2007 delta v8, used in *A Question of Balance* (Nordhaus, 2008)).

[4] Throughout the paper, the model version is the publicly available DICE-2007 delta v8, used in *A Question of Balance* (Nordhaus, 2008). It is written in GAMS and solved with CONOPT, and reproduces the published results. The GAMS model code, which features some intermediary calculations for the extensions introduced in this paper, is available on request.