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Preface

This book presents applications of optimal control theory and dynamic game theory in a broad range of problems associated with environmental economics. The book consists of 15 chapters, roughly half of which are based on research presented at the "12th Viennese Workshop on Optimal Control, Dynamic Games and Nonlinear Dynamics", which was held at the Vienna University of Technology (TU Wien) from May 30th to June 2nd, 2012. The workshop, which hosted more than 200 participants, was organized by Gustav Feichtinger, Josef L. Haunschmied, and Alexander Mehlmann, and two editors of this book, Gernot Tragler and Vladimir M. Veliov (all from TU Wien).

While that workshop provided the motivation to produce this book, the book cannot be considered as the proceedings thereof. Rather, for the purpose of providing a broader view of late-breaking applications of dynamic optimization in environmental economics, the chapters that stem from selected presentations at the workshop have been complemented by chapters from distinguished invited scientists in this field. The chapters are collected in two parts of the book and are ordered alphabetically according to the name of the first author within each part.

The first part, "Interactions between economy and climate", addresses the "economy $\mapsto$ pollution $\mapsto$ climate change $\mapsto$ economy" circle. The eight chapters in this part cover a variety of different approaches to modeling the feedbacks between the environment and the economy. For instance, some contributions describe the environment by its quality, concentration of pollutants, temperature, or a renewable resource stock, while others involve the environment only implicitly, represented by tax levy on emission or emission caps. Environmental policy instruments that are considered for the purpose of diminishing the climate change include (public) abatement, cap-and-trade, taxes, R&D, or technological change in several variants (e.g., exogenous versus endogenous, directed versus undirected).

The second part of the book, "Optimal extraction of resources", deals with optimal or rational utilization of renewable and non-renewable resources. The problems described in the seven chapters in this part include commercial fishery, forest management and biodiversity under climate change, the effects of resource exploitation and landowning on growth, export and import of fossil fuels, and harvesting of size-structured biological populations.

From a methodological perspective, the authors use various types of models and, therefore, various tools to analyze them appropriately. For instance, we find optimal control models in cases of a central planner, and dynamic games in cases of competing decision makers. While most of the models are deterministic, some also include stochastic uncertainties. In addition to standard problem formulations that rely on ordinary differential equations, there are also size-structured and spatially distributed systems. The tools used to analyze the problems include, but are not limited to, Pontryagin's maximum principle, nonlinear model predictive control techniques, nonlinear programming and the Karush-Kuhn-Tucker (KKT) theorem, the computation of Nash and Stackelberg equilibria, solution of Hamilton-Jacobi-Bellman equations, and numerical solution techniques such as the "Escalator Boxcar Train". Not only are some of the solution procedures innovative and sophisticated, but we also find complex solutions involving multiple equilibria and indeterminacy.

This book will be particularly interesting for economists, engineers, environmental managers, and applied mathematicians working on all kinds of dynamic optimization problems related to the interaction between environment, resources, and economic growth.

Finally, we wish to express our sincere gratitude to all of the authors of this book for their contributions, and the referees for their constructive suggestions on how to improve the individual chapters.

Vienna, Austria
November, 28, 2013

Elke Moser
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Contents

Part I
Interactions Between Economy and Climate

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Climate Change and Technical Progress: Impact of Informational Constraints

Anton Bondarev, Christiane Clemens, and Alfred Greiner

Abstract In this paper we analyse a growth model that includes environmental and economic variables as well as technological progress under different informational constraints on the behavior of economic agents. To simulate the informationally constrained economy, we make use of the non-linear model predictive control technique. We compare models with exogenous and endogenous technical change as well as directed and undirected endogenous technical change under different informational structures. We show that endogenous technical change yields lower environmental damages than exogenous technical change with a fully informed social planner. At the same time, welfare may rise or decline depending on the efficiency of the technology in use. In the case of directed technical change, a green growth scenario generates a smaller temperature increase that, however, goes along with less output and lower welfare. This holds both for the informationally constrained market economy and for the social optimum. We find that the effects of informational constraints, with respect to the climate system, increase with the degree of endogeneity of technology in the model.

1 Introduction

In this paper we develop the simple dynamic endogenous growth model of the world economy which takes into account environmental damages. There are a great many such models in the literature, starting with the seminal paper by Nordhaus (2007). Some of these models are of integrated assessment type (IAM) and employ the detailed description of the economy under consideration together with many sectors and parameters which are then estimated. Other types of models are of simpler

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structure and are employed to study some new approaches to the modeling of the environment in endogenous growth theory. In this second strand of literature there are two different approaches to modeling environmental damages and environmental threat for the economy: through the inclusion of environmental quality into the utility function of the representative household, as in the paper by Ligthart and Van Der Ploeg (1994), or through the assumption of productivity decreases due to the environmental degradation, or both. An example of such an approach is the paper by Bovenberg and Smulders (1995), where the notion of pollution-augmenting technical change is adopted. According to this classification, our paper belongs to the second approach.

The main focus of this paper is the influence of different forms of technical change on the evolution of the economy and on the environment under different informational regimes for the economy. Hence, there are two main departures from the majority of the literature on endogenous growth taking into consideration the environment. The first concerns the way the technological change is modeled and, the second, the way the representative household takes into account the environmental change in its decision making.

As concerns the first aspect, the technology in environmental models was usually modeled as an exogenous process of accumulation of knowledge according to some given function, without any influence from the part of the optimizing agent. Later on, there appeared a number of papers where the environmental variables are subject to the control of the agent together with the technology. These papers build up upon two well-known models of endogenous growth, namely that of Romer (1990) and that of Aghion and Howitt (1992). As an example for an endogenous growth model with environmental damages, based on variety expansion, one may take the paper by Barbier (1999), while papers by Grimaud (1999) and Grimaud and Rougé (2003, 2005) are based on the model of vertical innovations by Aghion and Howitt (1992). These and similar papers do not take into account the environmental friendliness of technologies being developed and deal only with productivity. At the same time, there is a discussion in the literature on the possibility of "green growth", where the productivity increase of the economy does not lead to environmental damages. In recent years, endogenous growth models have appeared that distinguish between "clean" and "dirty" technologies. This type of modeling uses the notion of directed technical change and the most recent example of such a literature is the paper by Acemoglu et al. (2012). The natural question one may ask is: what additional insight and implications follow from the inclusion of directed technical change into such a model. To answer it, we employ the same strategy as in the early paper by Smulders and Gradus (1996) and compare three simplified models in their predictions. We compare the results of the model with exogenous technical change, similar to the one employed in the paper of Bréchet et al. (2011), with those of undirected but endogenous technical change in the spirit of papers by Barbier (1999), Grimaud (1999) and with the outcome of the model featuring directed endogenous technical change with similar ideas as in Acemoglu et al. (2012). We come to the conclusion that in the absence of external stimuli, the planner will choose the more productive technology with higher environmental damages, rather than the cleaner one under directed technical change. At the same time, with undirected exogenous technical change, environmental damages may be lower than under directed change, given the "dirty" scenario of the economy.

Another aspect of interest for our research is the comparison of performance of the model under different informational regimes being allowed for. To this end, we employ the non-linear model predictive control (NMPC) approach which has been proposed for the environmental growth model in the paper by Bréchet et al. (2011), while developed earlier on in the literature on the NMPC technique, see the collection of contributions in Allgöwer and Zheng (2006) for reference. We compare the results of the model with an "optimal" (Pareto-optimal) behavior of the social planner, who cares about the environment to a full extent acting as a perfect-foresighted individual, with the outcome of a representative household with limited rationality, modeled as a receding planning horizon of the household.

As concerns the household sector, we assume a homogeneous household sector of mass one with household production, where each individual household has measure zero. Thus, the representative household has a negligible effect on aggregate emissions so that it neglects its emissions of greenhouse gases, which result as an external effect of production. Therefore, it does not invest in abatement but only chooses the optimal consumption share and the optimal share of investment in the creation of new technologies, which gives the laissez-faire or market solution. However, the household knows that the environment changes over time and, therefore, updates its optimal controls at certain discrete points in time, taking into account the new state of the environment. But, due to informational constraints, it does not continuously observe the changes in the environment. This makes our approach different from the usual modeling of externalities, where the representative household does not take into account the external effect but continuously observes the state of the environment, as in Greiner (1996, 2003) or more recently in Antoci et al. (2011).

It turns out that under receding horizon decision rules, the difference in terms of social welfare and environmental degradation between smart management of endogenous directed and undirected technological change and exogenously given pattern of technology is higher, compared to full information regime rules. At the same time, the directed technical change differs to a lesser extent from the undirected endogenous one (again in terms of welfare and environment) under informational constraints than under the full information regime. These differences in ordering of social welfare under different decision rules may help us to clarify the role that the management of technological progress plays with respect to the urgently desired switch of the equilibrium dynamics towards cleaner growth policies.

The rest of the paper is organised as follows. In the next section the formal description of all three versions of the model is given together with some necessary comments on the model structure. The main part is taken by the simulation results and their analysis, where the comparison between different models of technical change as well as different decision rules is made. The concluding section contains some brief discussion of results.

2 Model

We introduce the model of endogenous technical change in this section. First, we model undirected technical change by allowing for the productivity parameter, $A(t)$, to be controlled by the social planner, while leaving the emissions reduction technology, $e(t)$, exogenous which, later on, is controlled by the planner, too. The model presented below may be viewed as a straightforward extension of the model with exogenous technical change by Bréchet et al. (2011). We take this model with exogenous technical change as the benchmark.

2.1 Undirected Endogenous Technical Change

Consider first the model with only productivity being controlled by the social planner. There is also a gradual process of reduction of emission intensity, which is assumed to be exogenous for the time being. The social planner in the model represents some central authority (government). This planner has full information about the influence of economic activities on the environment. The economic part of the model is rather stylized and represented by the capital accumulation process. The climate change is represented by a pair of equations for the dynamics of temperature and greenhouse gas (GHG) concentrations.

The social planner optimally chooses the rate of consumption per capita and the rate of abatement activities to maximize social welfare and keep environmental degradation limited. The planner can also increase the productivity of the economy through R&D investments. With these assumptions the control problem of the planner contains 4 state variables (capital, temperature, GHG concentration and the state of technology) and 3 control variables (consumption rate, abatement rate and R&D investments per capita):

$$J^E = \max_{u,a,g} \left\{ \int_0^T \mathrm{e}^{-rt} \left[\frac{[u(t)Y(t)]^{1-\gamma}}{1-\gamma} \right] dt \right\} \tag{1}$$

s.t.

$$\dot{k}(t) = -\delta k(t) + \left[1 - u(t) - c_1\big(a(t)\big) - c_1\big(g(t)\big)\right] Y(t), \tag{2}$$

$$\dot{\tau}(t) = -\lambda \tau(t) + d\big(m(t)\big) = -\lambda \tau(t) + \eta \ln \frac{m}{m_0^*}, \tag{3}$$

$$\dot{m}(t) = -\nu m(t) + \big(1 - a(t)\big) e(t) Y(t), \tag{4}$$

$$\dot{x}(t) = \beta g(t) - \delta_2 x(t), \tag{5}$$

$$Y(t) = A^E(t)\phi\big(\tau(t)\big)k(t)^\alpha = A^E(t)\left(\frac{1}{1+\theta_1 \tau^{\theta_2}}\right)k(t)^\alpha, \tag{6}$$

$$A^E(t) = 1 + \omega x(t), \tag{7}$$

where:

J^E is the objective functional;
r is the discount rate;

$u(t)$	is the consumption rate per capita;
$Y(t)$	is the total output;
$k(t)$	is the total capital;
δ	is the depreciation rate of capital;
δ_2	is the depreciation rate of technology;
$a(t)$	is the abatement rate;
$g(t)$	are R&D investments;
$\tau(t)$	is the temperature increase from the preindustrial level;
λ	is the rate of temperature decrease due to natural causes;
$m(t)$	is the GHG concentration in the world's atmosphere;
ν	is the rate of recovery of the atmosphere due to natural absorption;
$e(t)$	is the reduction of intensity of emissions from economic activities;
$x(t)$	is the state of technology;
$A^E(t)$	is the productivity of the economy;
$\phi(\tau(t))$	is the damage function depending from the temperature increase;
α	is the parameter of capital productivity;
ω	is the rate of transformation of the current state of technology into the productivity of the economy.

In the model the evolution of state variables is given in the following way:

- Capital increases due to investments into capital, (2);
- Temperature increases as a function of the GHG concentration in the atmosphere, (3);
- GHG concentration increases due to economic activity in the economy (it is assumed that natural causes may be neglected), while the impact of economic activity is weakened through abatement and exogenous improvement in cleaning technologies, (4);
- Technology improves in a linear way from R&D investments while decreasing in the absence of such investments, (5);
- Output is of Cobb-Douglas type with labor supply normalized to unity with no population growth, (6);
- At last, productivity grows due to the transmission of a (fixed) proportion of technology into the production technology, (7).

It has to be noted that the original model of Bréchet et al. (2011) is easily obtained from this model by assuming a constant and linear increase in productivity, i.e. by substituting (7) with the linear technology $A^B = \kappa_1 t + \kappa_2$ and by setting $e(t) = \mathrm{e}^{-\iota_1 t - \iota_2}$ as well as dropping the (5) and the term $c_1(g(t))$ from (2).

The form of dynamics of technical progress itself is rather simple: the technology improves via the investments into the technological progress, $g(t)$ and declines in the absence of investments with some rate δ_2. Such a form of dynamics is rather simple and yet allows for the existence of steady state and endogenous technology.

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