UNIVERSITY OF NAIROBI

A SIMPLE COUPLED CLIMATE–ECONOMY–BIOSPHERE MODEL

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DECLARATION

Declaration by the candidate

I declare that this thesis has been composed by myself and has not been presented for a degree in any other university or for any other award. No part of this work should be reproduced without prior consent of the author, School of Mathematics (University of Nairobi) and/or Laboratoire de Météorologie Dynamique (Ecole Normale Supérieure, L'Université Pierre et Marie Curie, Paris 6).

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DEDICATION

This thesis is dedicated to GOD, all my teachers who showed me the beauty of knowledge, my mother – Maria Consolata Nyangige BORORO, my family, and humanity for their support on this journey.

"All men dream, but not equally. Those who dream by night in the dusty recesses of their minds wake in the day to find that it was vanity; but dreamers of the day are dangerous men, for they may act their dream with open eyes, to make it possible. This I did…"
(Seven Pillars of Wisdom by Lawrence TE 2006, p. 7)

… Coupled with the full knowledge that:
"A phrase is born into the world both good and bad at the same time. The secret lies in a slight, an almost invisible twist. The lever should rest in your hand, getting warm, and you can only turn it once, not twice." Isaac Babel, Russian short-story writer, 1894–1941.
(The Yale book of quotations by Shapiro FR 2006, p. 38)

… And:
Everything should be made as simple as possible, but not simpler…

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."
Albert Einstein

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ABSTRACT

The goal of this thesis is to build a reduced-complexity model of coupled climate─economy─biosphere interactions, which uses the minimum number of variables and equations needed to capture the fundamental mechanisms involved and can thus help clarify the role of the different variables and parameters. The Coupled Climate─Economy─Biosphere (CoCEB) model described herein takes an integrated assessment approach to simulating global change. By using an endogenous growth module with physical and human capital accumulation, this thesis considers the sustainability of economic growth, as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change. Various climate change mitigation policy measures are considered. While many integrated assessment models treat abatement costs merely as an unproductive loss of income, this thesis considers abatement activities also as an investment in increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system.

One of the major drawbacks of integrated assessment models is that they mainly focus on mitigation in the energy sector and consider emissions from land-use as exogenous. Since greenhouse gas emissions from deforestation and current terrestrial uptake are significant, it is important to include mitigation of these emissions in the biota sinks within integrated assessment models. Several studies suggest that forest carbon sequestration can help reduce atmospheric carbon concentration significantly and is a cost efficient way to curb the prevailing climate change. This thesis also looks at relevant economic aspects of deforestation control and carbon sequestration in forests as well as the efficiency of carbon capture and storage (CCS) technologies as policy measures for climate change mitigation.

Because full realistic coupled climate models are so complex, analyses of the various potential feedbacks between climate, economy, and biosphere have been rather limited. Potentially important mechanisms are better initially described in low or intermediate complexity models.

The CoCEB is a formal framework in which it is possible to represent in a simple way different elements of the coupled system and their interactions. The model developed, being an exercise in simplicity and not a predictive tool for climate change impacts, brings together and summarizes information from diverse literature on climate change mitigation measures and their associated costs, and allows comparing them in a coherent way.

The model is, of course sensitive, to the choice of key parameters and in particular the parameters setting the costs of the different means of climate change mitigation: the parameter values tested span the range of cost values found in literature.

The thesis shows that: i) investment in low-carbon technologies helps to reduce the volume of industrial carbon emissions, lower temperature deviations, and lead to positive effects in the long term economic growth; ii) low investment in CCS contributes to reducing industrial carbon emissions and to increasing gross domestic product (GDP), but further investment leads to a smaller reduction in emissions, as well as in the incremental GDP growth; iii) enhanced deforestation control contributes to a reduction in both deforestation emissions and atmospheric carbon dioxide concentration, thus reducing the impacts of climate change and contributing to a slight appreciation of GDP growth, an effect that is very small, though, compared to that of low-carbon technologies or CCS; and iv) the results in i) and ii) remain very sensitive to the formulation of technological improvements costs. To the contrary, the results for deforestation control are less sensitive to the formulation of its cost. A large range of hypotheses on these costs appear in the literature, and our modeling framework permitted to span this range and check the sensitivity of results The sensitivity study is not intended to make precise calibrations; rather, it is meant to provide a tool for studying qualitatively how various climate policies affect the economy.

RÉSUMÉ

L'objectif de cet étude est de construire un modèle de complexité réduite qui intègre les interactions et les rétroactions du système climat-économie-biosphère avec le minimum de variables et d'équations nécessaires afin de rendre les interactions dynamiques entre les différentes variables transparents. Le modèle couplé climat-économie-biosphère (CoCEB) décrit une approche d'évaluation intégrée pour simuler les changements planétaires. En utilisant un module de croissance endogène avec accumulation de capital physique et humaine, cette étude adresse le problème de la durabilité de la croissance économique. L’activité économique intensifie les émissions de gaz à effet de serre qui à leur tour causent des dommages économiques en raison du changement de climat. Diverses mesures de politique d'atténuation du changement climatique sont considérées. Alors que beaucoup IAM (*Integrated assessment models*) traitent les coûts de réduction des émissions (*abatement)* simplement comme une perte non productive de revenu, cet étude considère également les activités de réduction des émissions comme un investissement dans l'efficacité énergétique globale de l'économie et dans la diminution de l’ « intensité carbone » globale du système énergétique.

Un des inconvénients majeurs des IAM est qu'ils se concentrent principalement sur le secteur énergétique pour les mesures d’attenuation, et ne tiennent compte des émissions provenant de l'utilisation des terres que comme un forçage exogène. Cependant, les émissions de gaz à effet de serre due au changement de destination du sol, et l’effet de la séquestration de carbone par la terre a sont importantes, l effet des puits de biota doit donc être considéré. Plusieurs études suggèrent que le piégeage du carbone forestier peut aider à réduire de façon significative la concentration de carbone atmosphérique et qu’il est un moyen efficace en termes de coût pour freiner le changement climatique. Cette étude se penche donc également sur les aspects économiques de la séquestration de carbone du au contrôle du déboisement dans les forêts, at aussi de l’application généralisée des technologies de capture et stockage du carbone (CCS).

Du moment que les modèles climatiques couplés réalistes sont très complexes, les analyses des diverses rétroactions potentielles entre climat, économie et la biosphère ont été plutôt limitées. Mécanismes potentiellement importants sont mieux initialement décrites dans des modèles de complexité faible ou intermédiaire.

La CoCEB est un cadre formel dans lequel il est possible de représenter de façon simple les différents éléments du système couplé et leurs interactions. Le modèle mis au point, étant un exercice de simplicité et pas un outil de prédiction des impacts du changement climatique, rassemble et résume les différentes données trouvées dans la littérature sur les mesures de mitigation et les coûts y afférents, et permet de les comparer de façon cohérente.

Le modèle est sensible au choix des paramètres, en particulier au paramètres définissant les coûts des différents moyens d'atténuation de changement climatique: on a testé les valeurs des paramètres couvrant la gamme des valeurs de coût trouvé dans la littérature.

L'étude montre que: i) investissements dans les technologies à faible intensité de carbone contribue à réduire le volume des émissions de carbone industriel, réduire les écarts de température et entraîner des effets positifs de la croissance économique à long terme; ii) un faible investissement dans les CCS contribue à réduire les émissions de carbone industriel et à une augmentation de la croissance du PIB, mais un investissement supplémentaire a un effet inverse et diminue la réduction dans les émissions ainsi que l'incrément de croissance du PIB; iii) augmentation du contrôle de la déforestation contribue à réduire les émissions de la déforestation et$_2$ concentration de CO atmosphérique, ce qui réduit les impacts du changement climatique. Ces éléments contribuent à une légère appréciation de la croissance du PIB, mais cela reste très faible par rapport à l'effet des technologies à faible intensité carbonique ou CCS; iv) les résultats en i) et ii) restent très sensibles à la formulation du coût des améliorations technologiques. Un large éventail d'hypothèses sur ces coûts se trouve dans la littérature, notre modèle permet d'étendre cette gamme et vérifier la sensibilité des résultats. À l'inverse, les résultats pour le contrôle de la déforestation sont moins sensibles à la formulation de son coût. L'étude de sensibilité ne représente pas un calibrage précis ; au contraire, il est destiné à fournir un outil pour étudier qualitativement comment diverses politiques climatiques influent sur l'économie.

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OPERATIONAL DEFINATIONS OF TERMS AND CONCEPTS

Adaptation	Adjustment in natural or human systems to a new or changing environment.
Albedo	From the Latin *albus*, meaning white. It is the reflected fraction of incident radiation.
Biomass	The organic material both above-ground (stem, branches, bark, seeds and foliage) and below-ground (living biomass of life roots), and both living and dead.
Carbon cycle	The term used to describe the exchange of carbon (in various forms, e.g., as carbon dioxide) between the atmosphere, ocean, terrestrial biosphere and geological deposits.
Carbon sequestration	The process through which agricultural and forestry practices remove carbon dioxide (CO_2) from the atmosphere.
Climate system	The descriptionof the Earth in terms of its thermodynamical and biogeochemical state. This includes the climatic subsystems: the atmosphere, hydrosphere, cryosphere, land surface and biosphere.
CO_2 fertilization	The enhancement of plant growth as a result of elevated atmospheric CO_2 concentration.
Damage function	The relation between changes in the climate and reductions in economic activity relative to the rate that would be possible in an unaltered climate.
Deforestation	Those forestry practices or processes that result in a long-term land-use change from forest to agriculture or human settlements or other non-forest uses.
Energy balance	Averaged over the globe and over long time periods of at least 30 years, the energy budget of the *climate system* must be in balance. Because the climate

	system derives all its energy from the Sun, this balance implies that, globally, the amount of incoming *solar radiation* must on average be equal to the sum of the outgoing reflected solar radiation and the outgoing *infrared radiation* emitted by the climate system. A perturbation of this global radiation balance, be it human-induced or natural, is called *radiative forcing*.
Feedback	The phenomenon whereby the output of a system is fed into the input and the output is subsequently affected.
Forcing	A change in an internal or external factor, which affects the climate.
GDP	Gross Domestic Product. The value of all goods and services produced (or consumed) within a nation’s borders.
Greenhouse effect	The warming effect of the atmosphere caused by gases absorbing longwave radiation in the atmosphere.
Integrated assessment	A method of analysis that combines results and models from the physical, biological, economic and social sciences, and the interactions between these components, in a consistent framework, to project the consequences of climate change and the policy responses to it.
Kyoto Protocol	A United Nations Protocol of the Framework Convention for Climate Change that aims to reduce anthropogenic emissions of CO_2. It sets limits for anthropogenic CO_2 emissions with a view to reducing overall emissions to 5 per cent below 1990 levels by 2008 to 2012. See http://unfccc.int.
Land-use	The total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation).

Land-use change	A change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the *albedo*, *evapotranspiration*, *sources* and *sinks* of *greenhouse gases*, or other properties of the *climate system*, and may thus have an impact on *climate*, locally or globally.
Mitigation	Technological change and substitution that reduce resource inputs and emissions per unit of output with respect to climate change, mitigation means implementing policies to reduce GHG emissions and enhance sinks.
Parameterization	The method of incorporating a process by representation as a simplified function of some other fully resolved variables without explicitly considering the details of the process.
Photosynthesis	The metabolic process by which plants take CO_2 from the air (or water) to build plant material, releasing O_2 in the process.
Radiative forcing	A change in the average net radiation at the tropopause — the region between the troposphere and the stratosphere — brought about by changes in either the incoming solar radiation, or in the outgoing infrared radiation. Radiative forcing therefore disturbs the balance that exists between incoming and outgoing radiation. As the climate system evolves over time, it responds to the perturbation by slowly re-establishing the radiative balance. In general, positive radiative forcing tends (on average) to give rise to surface warming, whereas negative forcing tends (on average) to give rise to surface cooling.
Reforestation	Planting of *forests* on lands that have previously contained forests but that have been converted to some other use.

Sequestration	The process of increasing the carbon content of a carbon *reservoir* other than the *atmosphere*. Biological approaches to sequestration include direct removal of *carbon dioxide* from the atmosphere through *land - use change*, *afforestation*, *reforestation*, and practices that enhance soil carbon in agriculture. Physical approaches include separation and disposal of carbon dioxide from flue gases or from processing *fossilfuels* to produce hydrogen- and carbon dioxide-rich fractions and long-term storage in underground in depleted oil and gas reservoirs, coal seams, and saline *aquifers*.
Sinks	This is term used here to describe agricultural and forestry land that absorbs CO_2, the most important global warming gas emitted by human activities.
Solar constant	The amount of radiation from the Sun incident on a surface at the top of the atmosphere perpendicular to the direction of the Sun. Currently taken to be 1366 Wm^{-2} . Note that *S* can denote both 1366 Wm^{-2}, one quarter of this or the instantaneous top-of-the- atmosphere solar flux at a particular location. Context usually indicates which is meant.
Stefan–Boltzmann constant	s, having a value of 5.67 × 10^{-8} W m^{-2} K^{-4}, the constant of proportionality in Stefan's law.
Stefan's law	This is the relationship between the amount of energy radiated by a body and its temperature and is given by $E = sT^4$ where E is in Wm^{-2} and s is the Stefan–Boltzmann constant.
Surface air temperature	The temperature of the air near the surface of the Earth, usually determined by a thermometer in an instrument shelter about 1.3 m above the ground.

ABBREVIATIONS AND ACRONYMS

BAU	Business-as-Usual
C	Carbon
CCS	Carbon Capture and Sequestration
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
EBM	An Energy Balance Model. Probably the simplest model of the Earth system, based on the energy balance between the solar energy absorbed from the Sun and the thermal radiation emitted to space by the Earth
UNFCCC	The UN Framework Convention on Climate Change. Signed at the UN Conference on Environment and Development in 1992 and ratified in 1994. The FCCC has defined climate change to be only the human-induced effects (i.e. not natural variability) for its negotiations
GCM	A General Circulation Model or Global Climate Model. Initially used with reference to three-dimensional models of the atmosphere alone, the term has come to be loosely used to encompass three-dimensional models of the ocean (OGCMs) and coupled models
GEB	Global energy balance
GHGs	GreenHouse Gases
Gt	Gigatonnes
GtC	Gigatonnes of Carbon
IAMs	Integrated Assessment Models
IPCC	The Intergovernmental Panel on Climate Change. Established in 1988 and jointly sponsored by United Nations Environmental Programme and World Health

	Organization. Note that the IPCC is an assessment, not a research organization
KP	Kyoto Protocal
NGOs	Non-Government Organizations
REDD	Reduced Emissions from Deforestation and forest Degradation
TRF	Tons of reference fuel
UN	United Nations

CHAPTER 1

INTRODUCTION

1.1 Background to the problem

It is widely accepted that climate change will have major impacts on humankind. Depending on the magnitude of twenty-first century climate change, human societies and ecosystems are expected to be greatly affected by climate change (IPCC 2007b) and in particular by the frequency and intensity of extreme events (e.g., Changnon et al. 1996; Ciais et al. 2005; IPCC 2012a). Negative impacts are expected on water, food, human health and conflict (IPCC 2001b, p. 238; IPCC 2007b) and ultimately economic growth (Dell et al. 2014 and the citations therein; Nordhaus 2008; Stern 2007). Global carbon dioxide (CO_2) emissions, which are the largest contributor to anthropogenic climate change (Farmer and Cook 2013, p. 4; Mokhov et al. 2012; Stern 2008; Stott et al. 2000), have, to date, been highly correlated with economic output (Barker et al. 1995). As a result there is a negative feedback between climate change and economic growth that is mediated by CO_2 emissions: an increase in human wealth causes an increase in emissions and global warming, but the warming damages human wealth, slowing its rise or even making it fall. Although some integrated assessment models (IAMs) do include the climate─economy─biosphere feedback albeit only weakly (Nordhaus 2008), this feedback is typically neglected in a standard climate change assessment (Soden and Held 2006), which is largely a serial process going from socioeconomic scenarios to emissions to climate change to impacts (Cox and Stephenson 2007) (see Figure 1). A feasible sensitivity of the economy to the climate results in important emergent processes and feedbacks which need to be better understood inorder to address the climate change challenge.

This thesis focuses on the feedbacks between the climate, economy, and biosphere systems. Because full realistic coupled climate models are so complex, analyses of the various potential feedbacks have been rather limited. Thus, potentially important mechanisms are better initially described in low or intermediate complexity models. The use of a simple model in this thesis is meant to bring out the interplay between the climate, economy, and biosphere. General Circulation Models (GCMs) – by far the most sophisticated tools for performing global climate simulations – are ill-suited for the task of policy-oriented global and/or regional climate change assessment, in that the computational costs required in performing long-term simulations are largely prohibitive. Although substantial resources have been devoted to calibrating and building GCMs, there remains substantial uncertainty about many of their integral parts. There are many concerns about the role of clouds, the generation of precipitation, the role of ice, the interaction with oceans, soils, and the biosphere, and the role of other gases in the atmosphere. Further, the models still struggle to reproduce the current regional climates of earth (Mendelsohn and Rosenberg 1994). Global climate models are, in addition, unable to provide the degree of flexibility, ease-of-use, and transparency that policy-oriented modeling requires. Moreover, it is impossible for the moment to incorporate large-scale climate models into decision-analytic frameworks.

A simple model was selected for its ease and transparency. Simple models do not allow us to make a quantitative description of the coupled climate–economy–biosphere system dynamics; conversely, the study of such models makes it possible to understand the qualitative mechanisms of the coupled system processes and to evaluate their possible consequences.

The effort undertaken in this thesis operated under a critical chain of assumptions (Figure 1):

- ✓ human activities will result in greenhouse gas emissions
- ✓ atmospheric CO_2 concentrations will increase
- ✓ increased atmospheric CO_2 concentrations will cause atmospheric warming
- ✓ atmospheric warming will threaten living conditions

- ✓ threatened living conditions will require measures to mitigate the threat
- ✓ climate change mitigation strategies will affect climate change or its impacts through a variety of additional processes

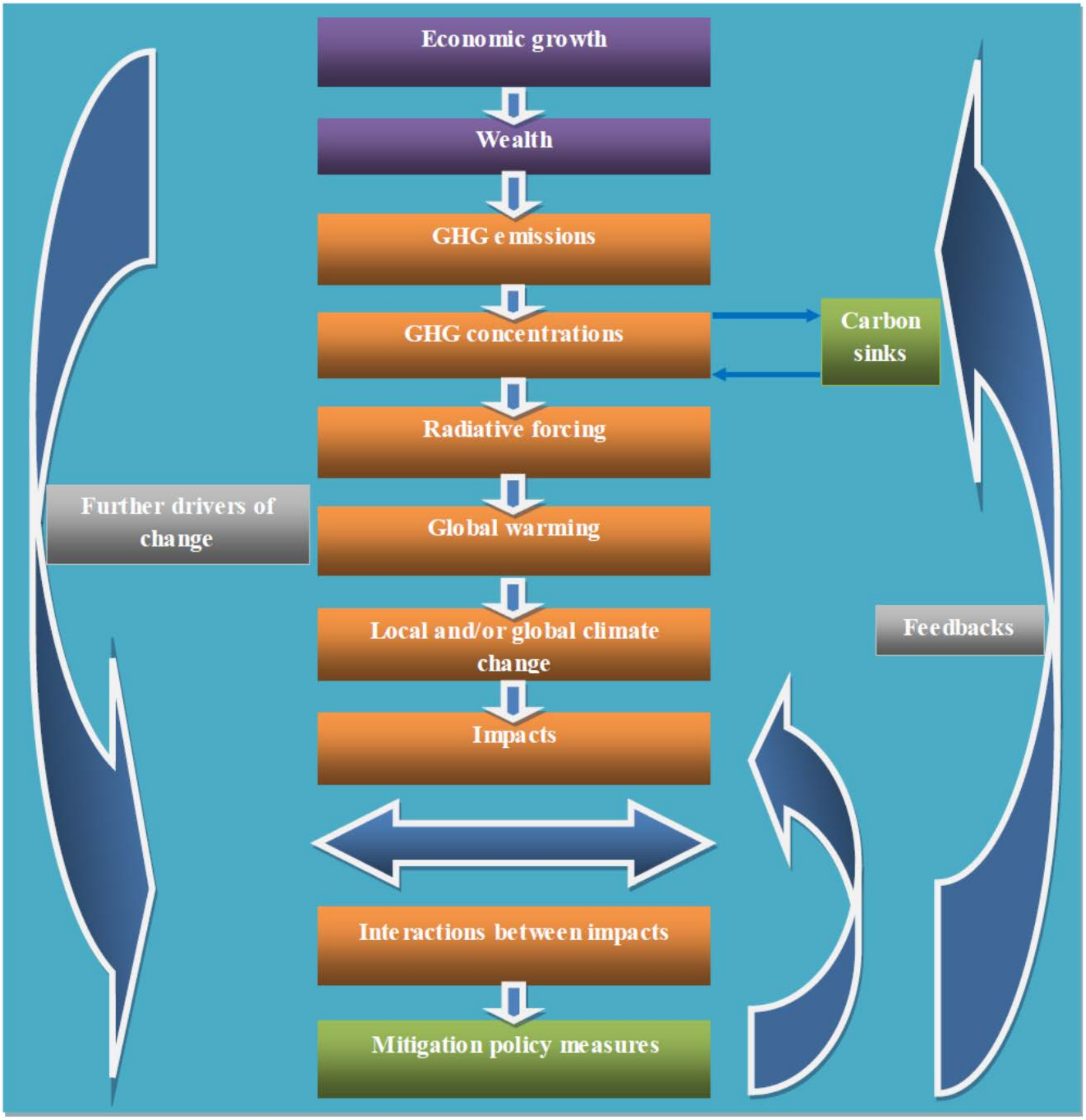

Fig. 1 Schematic of climate–economy–biosphere interactions (see also, Kellie-Smith and Cox 2013)

1.2 Statement of the problem and justification

Climate change represents one of the greatest environmental, social, and economic threats facing planet Earth today. The global climate has been changing due to human activities and is projected to keep changing even more rapidly. The consequences of climate change could be devastating, with increased atmospheric greenhouse gas concentrations resulting in large-scale, high-impact, non-linear, and potentially abrupt and/or irreversible changes in physical and biological systems (Mitchell 2009).

In developing countries, climate change will have a significant impact on the livelihoods and living conditions of the poor. Increasing temperatures and shifting rain patterns across the Earth's continents reduce access to food and create effects that impact regions, farming systems, households, and individuals in varying ways. Additional global changes, including changed trade patterns and energy policies, have the potential to exacerbate the negative effects of climate change on some of these systems and groups.

Thus, analyses of the biogeophysical, biogeochemical and socioeconomic factors that determine exposure, mitigation and/or adaptation, and the capacity to mitigate and/or adapt to climate change are urgently needed so that policymakers can make more informed decisions.

1.3 Objectives of the thesis

Global climate models offer the best approach to understanding the physical climate system. At various resolutions, they capture the basic behaviour of the physical processes that drive the climate. However, these models focus only on natural systems, and do not represent socio-economic systems that affect and are affected by natural systems. The most common approach to combining socio-economic and biophysical systems involves applying projected trends (scenarios) to “drive” the climate model. But such an approach disregards the existing dynamic feedbacks.

To bridge such gaps, the general objective of this research is to thesis the interactions and feedbacks between the climate, economy, and biosphere systems including the climate change related damages.

The specific objectives of the thesis are:

i) To develop a simple Coupled Climate─Economy─Biosphere (CoCEB) model.

ii) Application of the simple model to examine the interactions and feedbacks between the climate, economy, and biosphere systems.

iii) To analyze CoCEB's sensitivity to the implementation of the various climate change mitigation policy measures with their associated costs.

1.4 Significance of the thesis

The CoCEB is a formal framework in which it is possible to represent in a simple and clear way different elements of the coupled system and their interactions as well as feedbacks, while using the minimum number of variables and equations needed to capture the fundamental mechanisms involved and can thus help clarify the role of the different variables and parameters. The model developed, being an exercise in simplicity and transparency and not a predictive tool for climate change impacts, brings together and summarizes information from diverse fields in the literature on climate change mitigation measures and their associated costs, and allows comparing them in a coherent way.

1.5 Research methodology and outline of the thesis

The model describes the temporal dynamics of six variables: per capita physical capital K, per capita human capital H, the average global surface air temperature T, the CO_2 concentration in the atmosphere C, biomass/vegetation B, and industrial CO_2 emissions E_Y.

The thesis came up with a set of modules, which will be linked and will represent a crucial step in efforts to assess the influence that policy choice is likely to have on future climate. The thesis considered the nature of the relation between K, H, T, C, B, E_{Y}. Consequently by the use of a set of nonlinear, coupled Ordinary Differential Equations (ODEs), the temporal dynamics of these six variables are described by deriving a simple climate─economy─biosphere model composed of various modules – the climate module, economy module, biosphere module – that is used to explore the consequences of various climate change mitigation measures on economic growth.

The simplicity of the model makes it easier to clearly identify the relationships in the complex system. After the relationships are found, the mechanisms for these relationships are discussed and comparisons with observations or other studies, made, to evaluate their reasonability or correctness. The model structure and numerical analysis derives some of its parameters from previous climatic and economic studies (see, e.g., Eriksson 2013; Greiner 2004; Greiner and Semmler 2008; IPCC 2001a; Nordhaus 1994, 2007, 2013; Nordhaus and Boyer 2000; McGuffie and Henderson-Sellers 2005; Schwartz 2007, 2008; Uzawa 2003; van Wassenhove 2000; among others).

The thesis is outlined in Figure 2 below. It summarizes the various modules of the thesis. The next Section, Chapter 2, looks at the literature review.

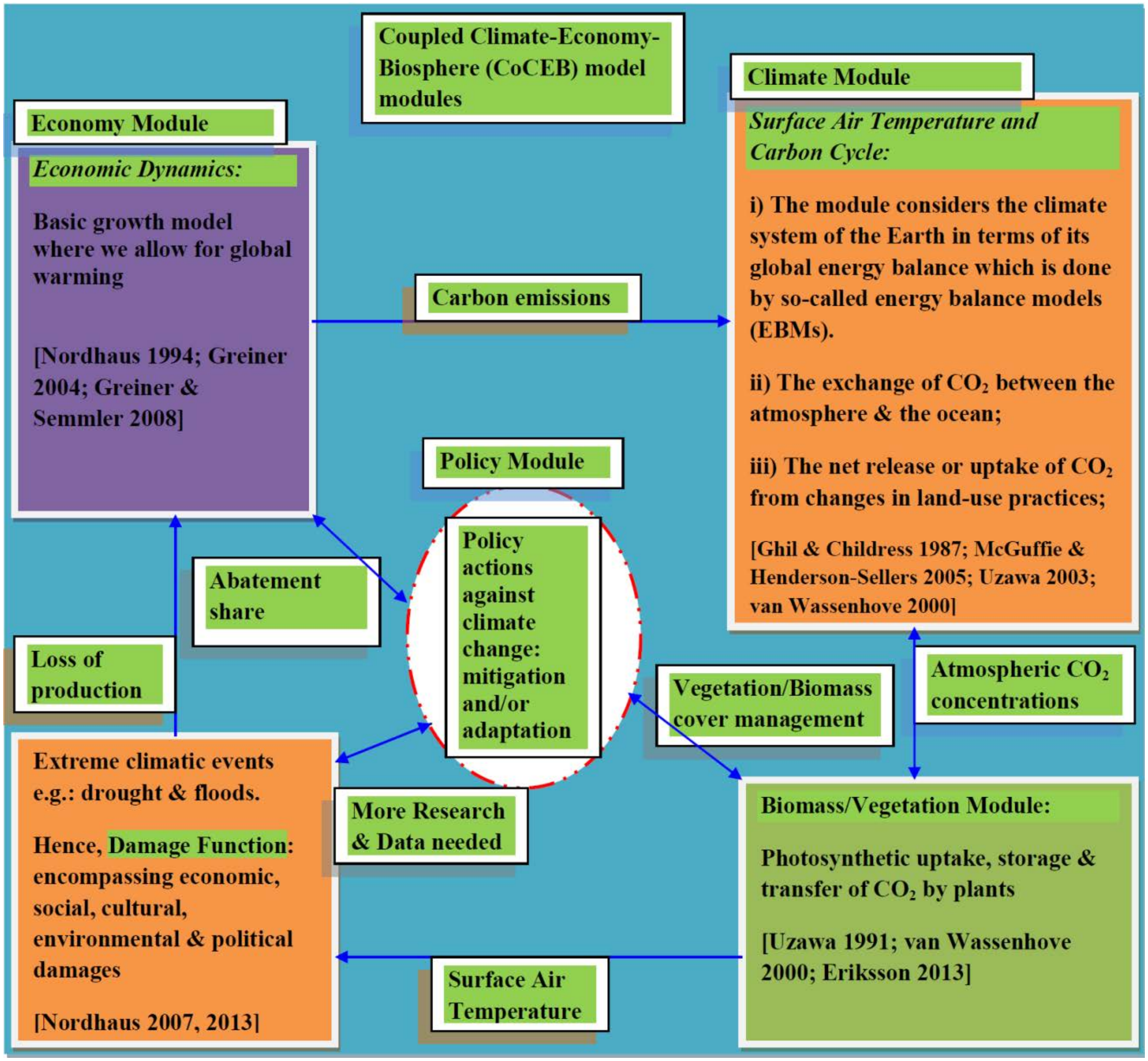

Fig. 2 The various modules of the thesis (see also, Edwards et al. 2005, p. 2, Figure 1.1)

CHAPTER 2

LITERATURE REVIEW

This chapter reviews some of the literature related to climate change modelling and integrated assessment modelling. Nowadays there are numerous climate change models; they function to predict future changes in climatic conditions and to help formulate mitigation policies. Integrated assessment models are especially useful in these regards, since they can provide insight into the interaction between different sectors of a larger system. The component models of individual sciences (natural or social) cannot do this.

2.1 Climate change and climate variability

Climate change and climate variability are two important characteristics of climate. According to United Nations Framework Convention on Climate Change (UNFCCC 1992), climate change is *a change of climate which is attributed directly or indirectly to any human activity that alters the composition of the global atmosphere and which is in addition to natural variability observed over comparable time periods*. On the other hand, climate variability is the *departure from normal or the difference in magnitude between climatic episodes.*

The history of scientific study of climate change is long. More than a century ago, for example, Fourier (1824, 1888) was the first to notice that the Earth is a greenhouse, kept warm by an atmosphere that reduces the loss of infrared radiation. The overriding importance of water vapor as a greenhouse gas was recognized even then. In the late 1890s, Arrhenius (1896) was the first to quantitatively relate the concentration of CO_2 in the atmosphere to global surface temperature. Given this long-standing history, one might lament the fact that - perhaps owing, in part, to the politically-charged nature of the topic – many people mistakenly assume that the science that underlies our current understanding of climatic change is, in some way, suspect or unreliable. Of course, the nature of the greenhouse debate is far too complex and multifaceted to lend itself well to simplistic “is it happening or isn’t it?” characterizations.

The vast evidence that the climate of the Earth is changing due to the anthropogenic increase in greenhouse gases (GHGs) is compiled in the successive reports of the Intergovernmental Panel on Climate Change (IPCC 1996a, 2001a, 2007a, 2013), CO_2 being the largest contributor (Farmer and Cook 2013, p. 4; Stern 2008; Stott et al. 2000). Typically, the effect of global warming on the economic system is modeled using integrated assessment models (IAMs). IAMs are motivated by the need to balance the dynamics of carbon accumulation in the atmosphere and the dynamics of de-carbonization of the economy (Nordhaus 1994a). A specific goal of these studies is to evaluate different abatement scenarios as to economic welfare and their effects on GHG emissions.

2.2 Integrated assessment modelling (IAM)

2.2.1 The emergence of IAMs as a science-policy interface

With the immense enhancement in computer technology, integrated modelling surfaced in the mid-1980s as a new paradigm for interfacing science and policy concerning complex environmental issues such as climate change. In the second half of the eighties, it was believed that integrated modelling would be the optimal way to interface science with policy. According to Parson (1994): “To make rational, informed social decisions on such complex, long-term, uncertain issues as global climate change, the capacity to integrate, reconcile, organize, and communicate knowledge across domains – to do integrated assessment – is essential.” Therefore, integrated assessment models are believed to produce insights that cannot be easily derived from the individual natural or social science component models that have been developed in the past (Weyant 1994); see also, Meyers (2012, pp. 5399–5428) and Rasch (2012, Ch. 8) for a further discussion.

According to Beltran et al. (2005, p. 70), Integrated Assessment (IA) can be defined as an interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole cause-effect chain of a problem can be evaluated from a synoptic perspective with two characteristics: (i) it should have added value compared to single disciplinary assessment; and (ii) it should provide useful information to decision makers.

2.2.2 Classification of IAMs

Nowadays IAMs are capable of reflecting a range of modelling approaches that aim to provide policy-relevant information, and most can be summarized by: (i) policy optimization that seeks optimal policies and (ii) policy evaluation models that assess specific policy measures. The complexity of optimization models is limited, however, because of the requirement of a large number of numerical algorithms in optimization. Therefore these models tend to be based on compact representations of both the socioeconomic and natural science systems. They thus contain a relatively small number of equations, with a limited number of geographic regions. Apart from policy optimization, policy evaluation models tend to be descriptive and can contain much greater modelling detail on bio-geo-physical, economic or social aspects. These models are often referred to as simulation models, and are designed to calculate the consequences of specific climate policy strategies in terms of a suite of environmental, economic, and social performance measures. An early example of this type of model is the Integrated Model to Assess the Global Environment (IMAGE) (Rotmans 1990; Alcamo et al. 1998).

Other policy evaluation models include Asian-Pacific Integrated Model (AIM), Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE), etc. These models are not subject to the constraints of optimization models, and therefore can incorporate greater complexity in their representations of natural and social processes at the regional scale without losing detail. Thus, they are generally applied to comparisons of the consequences (e.g., regional economic and environmental impacts) of alternative emissions scenarios. But even with these detailed descriptive capabilities, they are not appropriate to optimize the economic activities of the energy-economy sector.

2.2.3 Application of integrated assessment models

Integrated Assessment Modelling is usually comprehensive, but it produces less detailed models than conventional climate- or socio-economic-centred approaches. It is based on an understanding that feedbacks and interconnections in the climate-society-biosphere system drive its evolution over time (Davies and Simonovic 2008). Rotmans et al. (1997, p. 36) state that integrated assessments "are meant to frame issues and provide a context for debate. They analyze problems from a broad, synoptic perspective."

Integrated assessment modelling is not a new concept; it rather has a long history of being applied to many problems. Over the past decade or so, integrated assessment models (IAMs) have been widely utilized to analyze the interactions between human activities and the global climate (Weyant et al. 1996). The first IPCC report referenced two IAMs, the Atmospheric Stabilization Framework from US Environmental Protection Agency (EPA) and the Integrated Model for the Assessment of the Global Environment (IMAGE) model from the Netherlands (van Vuuren et al. 2006a). These were employed to assess the factors controlling the emissions and concentrations of GHGs over the next century. Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) was then developed to account ocean heat transport and a carbon cycle component to respond the land-use change; it is a multi-box energy balance model (Meinshausen et al. 2008). Later, MAGICC modelling framework became a foundation for the IPCC process, as it can easily show the climate implications of different emissions scenarios and can be benchmarked to have climate responses that mimics those of any of the GCMs.

Rotmans et al. (1997), mention that the integrated assessment approach allows for an exploration of the interactions and feedbacks between subsystems and provides flexible and fast simulation tools. It also identifies and ranks major uncertainties, and supplies tools for communication between scientists, the public, and policy makers. Davies (2007) provides some examples of integrated assessment models including the Integrated Model to Assess the Greenhouse Effect, IMAGE 2.0 (Alcamo et al. 1994), the Asian Pacific Integrated Model, AIM (Matsuoka et al. 1995), the Model for Evaluating Regional and Global Effects of GHG reduction policies, MERGE (Manne et al. 1995), the Tool to Assess Regional and Global Environmental and health Targets for Sustainability, TARGETS (Rotmans and de Vries 1997), the Integrated Global System Model, IGSM (Prinn et al. 1999), Integrated Climate Assessment Model, ICAM (Dowlatabadi 2000), the Dynamics Integrated Climate-Economy model, DICE (Nordhaus and Boyer 2000), the Feedback-Rich Energy-Economy model, FREE (Fiddaman 1997; Fiddaman 2002), and World3 (Meadows et al. 2004). The list of IAMs and Computable General Equilibrium (CGE) models used in climate policy analyses is long. The reader can refer to Ortiz and Markandya (2009) and Stanton et al. (2008) for a literature review of some of these models.

Most IAMs consist of (i) an economy module in which the interactions among economic sectors and agents are represented; (ii) a climate module representing the relationships between GHG emissions and concentrations and temperature changes; and (iii) predetermined relationships between both modules; i.e. damage functions representing the impact of temperature changes in the economy, and abatement cost functions summarizing the available climate change mitigation options. The level of details employed in each of these components characterizes and differentiates the existing models (Ortiz et al. 2011).

It has been predicted that global climate change will have significant impacts on society and the economy, and that the adaptation measures to tackle global climate change will be accompanied with very large economic burden. It is estimated that GHG emissions will increase to over one-half of total global emissions by the end of the next century (Akhtar 2011, p. 42). The Integrated Assessment Model (IAM) provides a convenient framework for combining knowledge from a wide range of disciplines; it is one of the most effective tools to increase the interaction among these groups.

2.2.4 Challenges for IAM studies

The foremost challenge for IAM Studies is the integration of the natural and socioeconomic systems in order to better model the relationship between human activities and the global environment. To the present, many integrated assessment models share the same basic framework. Whether current IAMs have reached a level of development where they can serve as the adequate basis for judgments in formulating actual global environmental measures is debatable. Modellers appear to agree, however, that for the most part the framework itself is acceptable. The integrated assessment of global environmental issues from the perspectives of the natural and social sciences is not a field of learning involving the pursuit of truth. Rather, it is a practical science that aims at providing useful guidance to policy makers seeking to establish rules and policies that help smooth the relationships between natural rule, the global environment and humanity. Conventionally, it is possible to encapsulate the relationships between such practical scientific studies and the real world in a relatively simple framework.

Any attempt to represent fully a complex issue and its numerous interlinkages with other issues in a quantitative modelling framework is doomed to failure (Rotmans and van Asselt 2001). However, even a simplified integrated assessment model can provide valuable insight into certain aspects of complex issues. Through their intersectoral links and communication facilities, IAMs can provide more accurate representations of such problems as climate change than those studies based on a conventional modelling framework. IAMs thus remain a very useful tool for decision makers, scientists– especially in the field of climate change studies.

In analyzing implications of climate policies, these models often assume that the growth rate of the economy is exogenously given, and feedback effects of lower GHGs concentrations in the atmosphere on economic growth are frequently neglected. For example, in Nordhaus and Boyer (2000) different abatement scenarios are analyzed where the growth rate of the economy is assumed to be an exogenous variable and the results are compared with the social optimum. Also, the fundamental alterations in wealth holdings are systematically downplayed by the practices of current integrated assessment modeling (Decanio 2003; Kirman 1992, p. 132).

2.2.5 Improvements of IAMs

There are several aspects in which IAMs need to be improved. Besides the need for better data on expected economic damages of climate change, future research on IAMs should consider:

- ✓ ***Economic modeling in developing countries***. Most current IAMs do not match the economic and social organization of developing countries well (Carraro 2002). This leads to biases in global assessments where climate change mitigation and impacts are evaluated in developing countries as if their economies work like those of developed countries.
- ✓ ***Endogenous Technical Change***. Most IAMs models have considered technical change as an exogenous variable, where emission intensity of output is expected to decrease based on historical records (Kelly and Kolstad 1999). But, technical change might be critically important in GHGs mitigation scenarios. For example, the development of inexpensive electric automobiles or solar power might reduce significantly GHGs emissions at low cost. Further research is needed in order to incorporate endogenous innovation in climate models.
- ✓ ***Specifying Regulation Instruments*** (Kelly and Kolstad 1999). Most IAMs calculate optimal carbon taxes for achieving emission reduction targets. But, the impact of recycling such tax revenues needs to be evaluated. Also, regulation instruments have associated monitoring costs

and penalties for non-compliance which would reduce the overall efficiency of mitigation strategies.

- ✓ ***Adjustment to Climate Change*** (Kelly and Kolstad 1999). Agents within the economy would respond to global warming in order to reduce its impacts. For example, given changes in rainfall and precipitation, farmers could modify crop choice in order to reduce the losses caused by climate change. Also, migration patterns and urbanization in developing countries might be modified in such a way that areas highly vulnerable to climate change would limit their growth.
- ✓ ***Include carbon mitigation in sinks***. One of the major drawbacks of IAMs is that they mainly focus on mitigation in the energy sector (van Vuuren et al. 2006b, p. 166). For example, the RICE (Regional Dynamic Integrated model of Climate and the Economy) and DICE (Dynamic Integrated model of Climate and the Economy) (Nordhaus and Boyer 2000) models consider emissions from land use as exogenous (see also, Tol 2010 p. 97). But, GHGs emissions from land use and current terrestrial uptake are significant, so including GHGs mitigation in sinks is something to be considered within IAMs (Wise et al. 2009).

2.2.6 This thesis

This thesis looks at the interaction between global warming and economic growth, along the lines of the Dynamic Integrated model of Climate and the Economy (DICE) of Nordhaus (1994a), with subsequent updates in Nordhaus and Boyer (2000), Nordhaus (2007, 2008, 2010, and 2013a). Greiner (2004) (see also Greiner and Semmler 2008) extended the DICE framework by including endogenous growth, to account for the fact that environmental policy affects not only the level of economic variables but also the long-run growth rate. Using the extended DICE model, Greiner argues that higher abatement activities reduce GHG emissions and may lead to a rise or decline in growth. The net effect on growth depends on the specification of the function between the economic damage and climate change.

Since anthropogenic GHGs are the result of economic activities, the main shortcoming in Greiner's (2004) approach is that of treating industrial CO_2 emissions as constant over time. Another problematic aspect of Greiner's emissions formulation is its inability to allow for zero abatement activities. In fact, his formulation only holds for a minimum level of abatement.

This thesis addresses these issues by using a novel approach to formulating emissions that depend on economic growth and vary over time; in this approach, abatement equal to zero corresponds to Business As Usual (BAU). To do so, this work uses logistic functions (Akaev 2012; Sahal 1981; see also, Probert et al., 2004, p. 108, and references therein) that yield the global dynamics of carbon intensity, i.e. of energy emissions per unit of energy consumed, and of energy intensity, i.e. of energy use per unit of aggregate gross domestic product (GDP) throughout the whole 21st century (Akaev 2012).

The thesis further uses the extended DICE modeling framework by considering both human and physical capital accumulation, in addition to the GHG emissions, as well as a ratio of abatement spending to the tax revenue or abatement share (see also, Greiner 2004; Greiner and Semmler 2008). The methodology utilized can analytically clarify the mutual causality between economic growth and the climate change–related damages and show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Hannart et al. 2013; Metz et al. 2007). The thesis will use the abatement share to invest in the increase of overall energy efficiency of the economy (Diesendorf 2014, p. 143) and decrease of overall carbon intensity of the energy system. It will be shown below that over the next few decades, up to the mid-21st century, mitigation costs do hinder economic growth, but that this growth reduction is compensated later on by the having avoided negative impacts of climate change on the economy; see also Kovalevsky and Hasselmann (2014, Figure 2).

The thesis also introduces CO_2 capturing and storing (CCS) technologies and reduction of deforestation, as well as increasing photosynthetic biomass sinks as a method of controlling atmospheric CO_2 and consequently the intensity and frequency of climate change related damages.

This move is necessitated on one part by the fact that most of the scenario studies that aim to identify and evaluate climate change mitigation strategies (see, e.g., Hourcade and Shukla 2001; Morita and Robinson 2001) focus on the energy sector (van Vuuren et al. 2006b, p. 166). Examples of studies that focus on the energy sector are the RICE (Regional Dynamic Integrated model of Climate and the Economy) and DICE (Dynamic Integrated model of Climate and the Economy) (Nordhaus and Boyer 2000) models which consider emissions from land-use as exogenous (see also, Tol 2010 p. 97). Nevertheless, GHG emissions from deforestation and current terrestrial uptake are significant, so including GHG mitigation in the biota sinks has to be considered within integrated assessment models (IAMs), cf. Wise et al. (2009).

Several studies provide evidence that forest carbon sequestration can reduce atmospheric CO_2 concentration significantly and could be a cost-efficient way for curbing climate change (e.g., Bosetti et al. 2011; Gullison et al. 2007; Tavoni et al. 2007; Wise et al. 2009). Again, most earlier studies have not considered the more recent mitigation options currently being discussed in the context of ambitious emission reduction, such as hydrogen and carbon capture and storage (CCS); see Edmonds et al. (2004), IEA (2004) and IPCC (2005). Given current insights into climate risks and the state of the mitigation literature, then, there is a very understandable and explicit need for comprehensive scenarios that explore different long-term strategies to stabilize GHG emissions at low levels (Metz and van Vuuren 2006; Morita et al. 2001). This thesis works towards this direction by studying relevant economic aspects of deforestation control and carbon sequestration in forests, as well as the widespread application of CCS technologies as alternative policy measures for climate change mitigation.

The Coupled Climate─Economy─Biosphere (CoCEB) model is not intended to give a detailed quantitative description of all the processes involved, nor to make specific predictions for the latter part of this century. It is a reduced-complexity model that attempts to incorporate the climate─economy─biosphere interactions and feedbacks, while using the smallest number of variables and equations needed to capture the main mechanisms involved in the evolution of the coupled system. We merely wish to trade greater detail for more flexibility in the analysis of the dynamical interactions between the different variables. The modeling framework here brings together and summarizes information from diverse fields in the literature on climate change mitigation measures and their associated costs, and allows comparing them in a coherent way. The need for a hierarchy of models of increasing complexity is an idea that dates back – in the climate sciences – to the beginnings of numerical modeling (e.g., Schneider and Dickinson 1974), and has been broadly developed and applied since (Ghil 2001, and references therein).

The thesis seeks to show that:

(i) Investment in low-carbon technologies helps to reduce the volume of industrial CO_2 emissions, lower temperature deviations, and lead to positive effects in economic growth.

(ii) Low investment in CCS contributes to reducing industrial carbon emissions and to increasing GDP growth, but further investment leads to a smaller reduction in emissions, as well as in the incremental GDP growth.

(iii) Enhanced deforestation control contributes to a reduction in both deforestation emissions and atmospheric CO_2 concentration, thus reducing the impacts of climate change and contributing to a slight appreciation of GDP growth, but this effect is very small compared to that of implementing low carbon technologies or CCS.

(iv) The result in (ii) is very sensitive to the formulation of CCS costs. To the contrary, the results for deforestation control are less sensitive to the formulation of its cost.

A large range of hypotheses on CCS costs appears in the literature, and our modeling framework permits to span this range and check the sensitivity of results.

The sensitivity study carried out is not intended to make precise calibrations; rather, the study wants to provide adiagnostic tool for studying qualitatively how various climate policies affect the economy.

The next chapter describes the theoretical model, detailing the additions with respect to Nordhaus (2013a), Greiner (2004) and Greiner and Semmler (2008), introduces the biomass equation and the effect on the carbon emissions of CCS and of deforestation control. Chapter 4 presents the numerical simulations and their results. In Chapter 5, we test the sensitivity of the results to key parameters. Chapter 6 summarizes, discusses the results, and formulates our conclusions with caveats and avenues for future research.

CHAPTER 3

MODEL DESCRIPTION

3.1 Climate module

The time evolution of the average surface temperature T (SAT) on Earth is modeled via an energy balance equation given by

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{(1-\alpha_{\mathrm{T}})\mathrm{Q}}{4c_{\mathrm{h}}} - \frac{\varepsilon\sigma_{\mathrm{T}}\tau_{\mathrm{a}}}{c_{\mathrm{h}}}T^4 + \frac{6.3\beta_1(1-\xi)}{c_{\mathrm{h}}}\mathrm{In}\left(\frac{C}{\hat{C}}\right), \tag{1}$$

see, for instance, Ghil and Childress (1987, Ch. 10), Hans and Hans (2013, Ch. 2) or McGuffie and Henderson-Sellers (2005, p. 81–85; 2014). Here the first and second terms on the right-hand side are incoming and outgoing radiative fluxes respectively, while the third term is radiative forcing due to increase in GHGs (Greiner and Semmler 2008; Kemfert 2002); σ_{T} is the Stefan-Boltzmann constant, τ_{a} the infrared (long-wave) transmissivity of the atmosphere, ε the emissivity that gives the ratio of actual emission to blackbody emission, α_{T} the mean planetary albedo, Q is the average solar constant. The specific heat capacity c_{h} of Earth is largely determined by the oceans (Levitus et al. 2005) and it is taken equal to 16.7 $\mathrm{Wm}^{-2}\mathrm{K}^{-1}$ (Schwartz 2007, 2008), which corresponds to an ocean fractional area of 0.71 and a depth of $150\ \mathrm{m}$ of the ocean mixed layer. The current CO_2 concentration C is given in gigatons of carbon (GtC, 1 Gt = 10^{15} grams) and $\hat{C}$ is the pre-industrial CO_2 concentration. All the feedbacks, are represented in this highly idealized model by the factor β_1 , which is assumed to take values between 1.1 and 3.4 (Greiner and Semmler 2008, p. 62); in this thesis, it was assumed that $\beta_1 = 3.3$. The parameter $\xi = 0.23$ captures the fact that part of the warmth generated by the greenhouse effect is absorbed by the oceans and transported from their upper layers to the deep sea (Greiner and Semmler 2008). The other parameters have standard values that are listed in Table 1.

At equilibrium, that is for $\mathrm{d}T/\mathrm{d}t = 0$, Equation (1) gives an average SAT of 14 ^{0}C for the pre-industrial GHG concentration, i.e. for $C = \hat{C}$. Doubling the CO_2 concentration in Equation (1) yields an increase of about 3.3 ^{0}C in equilibrium temperature, to 17 ^{0}C. This increase lies within the range of IPCC estimates, between 1.5 and 4.5 ^{0}C (Charney et al. 1979; IPCC 2001a, p. 67; IPCC 2013) with a best estimate of about 3.0 ^{0}C (IPCC 2007a, p.12).

The thesis represents the evolution C of the concentration of CO_2 in the atmosphere, following Uzawa (2003) and Greiner and Semmler (2008), as

$$\frac{dC}{dt} = \beta_2 E_{\mathrm{Y}} - \mu_{\mathrm{o}}\left(C - \hat{C}\right), \tag{2}$$

where E_{Y} is industrial CO_2 emissions. The excess C above pre-industrial level is reduced by the combined effect of land and ocean sinks. The inverse μ_{o} of the atmospheric lifetime of CO_2 is estimated in the literature to lie within an uncertainty range that spans 0.005–0.2 (IPCC 2001a, p. 38); The thesis takes it here to equal $\mu_{\mathrm{o}} = 1/120 = 0.0083$, i.e. closer to the lower end of the range (IPCC 2001a, p. 38; Nordhaus 1994a, p. 21). The fact that a certain part of GHG emissions is taken up by the oceans and does not remain in the atmosphere is reflected in Equation (2) by the parameter β_2.

3.2 Economy module

In Greiner (2004) and Greiner and Semmler (2008) the per capita GDP, Y, in USD_{1990}, is given by a modified version of a constant-return-to scale Cobb-Douglas production function (Cobb and Douglas 1928),

$$Y = \mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T - \hat{T}\right). \tag{3}$$

Here K is the per capita physical capital, H is the per capita human capital, $\mathrm{A} > 0$ the total factor of productivity, $0 < \alpha < 1$ is the capital share, $D\left(T - \hat{T}\right)$ is the damage, expressed as a function of the temperature difference due to climate change. The damage function is described in Subsection (3.3.3) below.

The economy income identity in per capita variables is given by

$$Y - X = I + M_{\mathrm{E}} + G_{\mathrm{E}}, \tag{4}$$

with $X = \tau Y$ the (per capita) tax revenue, $0 < \tau < 1$ the per annum tax rate, I investment, M_{E} consumption, and G_{E} abatement activities. This means that national income after tax is used for investment, consumption, and abatement. The thesis assumes that G_{E} is expressed as a fraction of X,

$$G_{\mathrm{E}} = \tau_{\mathrm{b}} X = \tau_{\mathrm{b}} \tau Y, \tag{5}$$

with $0 \le \tau_{\mathrm{b}} < 1$ the ratio of per annum abatement share, used as a policy tool. Consumption is also expressed as a fraction of Y after tax, that is,

$$M_{\mathrm{E}} = c\left(1 - \tau\right)Y, \tag{6}$$

with $0 < c < 1$ the global annual consumption share.

The accumulation of per capita physical capital K is assumed to obey

$$\frac{\mathrm{d}K}{\mathrm{d}t} = Y - X - M_{\mathrm{E}} - G_{\mathrm{E}} - \left(\delta_{\mathrm{K}} + n\right)K, \tag{7}$$

the logistic-type human population growth rate $0 < n < 1$ is given, in turn, by

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \left(\frac{1}{1 - \delta_{\mathrm{n}}} - 1\right)n, \tag{8}$$

with δ_{n} being the per year decline rate of n, and δ_{K} the per year depreciation rate of physical capital. Substituting the definitions of Y, X, M_{E}, and G_{E} into Equation (7) the thesis gets

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\left[1-\tau\left(1+\tau_{\mathrm{b}}\right)-c\left(1-\tau\right)\right]-\left(\delta_{\mathrm{K}}+n\right)K\,. \tag{9}$$

For physical capital to increase, $\mathrm{d}K/\mathrm{d}t > 0$, the parameters must satisfy the inequality $0 < \left[\tau\left(1+\tau_{\mathrm{b}}\right)+c\left(1-\tau\right)\right] < 1$. Now, proceeding as above for K, I assume that the per capita human capital H evolves over time as

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \varphi\left\{\mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\left[1-\tau\left(1+\tau_{\mathrm{b}}\right)-c\left(1-\tau\right)\right]\right\}-\left(\delta_{\mathrm{H}}+n\right)H\,, \tag{10}$$

here $\varphi > 0$ is a coefficient that determines how much any unit of investment contributes to the formation of the stock of knowledge and δ_{H} gives the depreciation of knowledge.

Note that the thesis takes, as a starting point, the Solow-Swan approach (Greiner and Semmler 2008; Solow 1956; Swan 1956), in which the share of consumption and saving are given. This is done because the thesis wants to focus on effects resulting from climate change, which affect production as modeled in Equations (3)–(10) and, therefore, neglect effects resulting from different preferences.

The formulation assumes, furthermore, that government spending, except for abatement, does not affect production possibilities. Emissions of CO_2 are a byproduct of production and hence are a function of per capita output relative to per capita abatement activities. This implies that a higher production goes along with higher emissions for a given level of abatement spending. This assumption is frequently encountered in environmental economics (e.g., Smulders 1995). It should also be mentioned that the emission of CO_2 affect production indirectly by affecting the climate of the Earth, which leads to a higher SAT and to an increase in the number and intensity of climate-related disasters (see, e.g., Emanuel 2005; Min et al. 2011).

3.3 Industrial CO_2 emissions

In Greiner (2004) and Greiner and Semmler (2008), emissions E_{Y} are formally described, as a function of the production Y, by

$$\left(\frac{aY}{G_{\mathrm{E}}}\right)^{\gamma}=\left(\frac{aY}{\tau_{\mathrm{b}}\tau Y}\right)^{\gamma}=\left(\frac{a}{\tau_{\mathrm{b}}\tau}\right)^{\gamma}, \tag{11}$$

here $\gamma>0$ is a constant and $a>0$ a technology index that describes how polluting a given technology is. Note that Equation (11) is defined only for τ_{b} different from zero; hence, it does not consider a no-abatement or BAU scenario. Moreover, Equation (11) also gives constant emissions over time even when the economic activity is changing, which is unrealistic. Here, the thesis uses instead a formulation of emissions E_{Y} that vary over time and in which abatement can be let to be zero.

Specifically, the thesis uses the Kaya-Bauer identity (Bauer 2005; Kaya 1990) that breaks down CO_2 emissions E_{Y} (in GtCyr^{-1}) into a product of five components: emissions per unit of energy consumed (carbon intensity of energy), energy use per unit of aggregate GDP (energy intensity), per capita GDP, human population, and carbon emission intensity, as shown below:

$$\begin{aligned} E_{\mathrm{Y}} &= \left(\frac{E_{\mathrm{tot}}}{energy}\right)\left(\frac{energy}{\bar{Y}}\right)\left(\frac{\bar{Y}}{L}\right)L\left(\frac{E_{\mathrm{Y}}}{E_{\mathrm{tot}}}\right) \\ &= c_{\mathrm{c}}e_{\mathrm{c}}YL\kappa_{\mathrm{ccs}} \\ & \quad \sigma YL\kappa_{\mathrm{ccs}}. \end{aligned}$$

Here $\bar{Y}$ is aggregate GDP, $Y=\left(\bar{Y}/L\right)$ is per capita GDP, L is the human population, $c_{\mathrm{c}}=E_{\mathrm{tot}}/energy$ is the carbon intensity of energy, $e_{\mathrm{c}}=energy/\bar{Y}$ is the energy intensity, $c_{\mathrm{c}}e_{\mathrm{c}}=E_{\mathrm{tot}}/\bar{Y}=\sigma$ is the ratio of industrial carbon emissions to aggregate GDP or the economy carbon intensity, $E_{\mathrm{Y}}/E_{\mathrm{tot}}=\kappa_{\mathrm{ccs}}$ is the fraction of emissions that is vented to the atmosphere and involves CCS.

The E_{Y} level also depends on abatement activities, as invested in the increase of overall energy efficiency in the economy and decrease of overall carbon intensity of the energy system. The case of $\tau_{\mathrm{b}} = 0$ in Equation (5) corresponds to unabated emissions, i.e. BAU. Emissions are reduced as the abatement share increases. Taking the natural logarithms and differentiating both sides of the Kaya-Bauer identity yields

$$\frac{\mathrm{d}E_{\mathrm{Y}}}{\mathrm{d}t} = \left[g_{\sigma} + g_{\mathrm{Y}} + n + g_{\mathrm{ccs}}\right] E_{\mathrm{Y}}, \tag{12}$$

where g_{σ} is the growth rate of σ, g_{Y} is the growth rate of Y, n is the population growth rate and g_{ccs} is the CCS growth rate. If CCS is applied, then $E_{\mathrm{Y}} < E_{\mathrm{tot}}$. There are many concerns and uncertainties about the CCS approach and it is usually not taken as a real sustainable and environmental friendly mitigation option to reduce emissions over a longer period (Tol 2010).

The thesis now formulates the technology-dependent carbon intensity σ. The thesis follows the approach of Sahal (1981), who models the replacement of one technology by another using a logistic law. The energy intensity e_{c}, in tons of reference fuel (TRF)/USD1000 of $\overline{Y}$, is the share of hydrocarbon-based energy (coal, oil, and natural gas) in the global energy balance (GEB) of the twenty-first century. Its dynamics are described by a descending logistic function (Akaev 2012),

$$e_{\mathrm{c}} = f_{\mathrm{c}}\left(1 - \frac{r\exp(\psi t)}{1 + r\left(\exp(\psi t) - 1\right)}\right), \tag{13}$$

here the thesis takes 1990 as the time when the use of renewable energy sources (biomass and wastes, hydropower, geothermal energy, wind energy, and solar energy) and biofuels became significant in the GEB. The multiplier $f_{\mathrm{c}} = 0.881$ corresponds to 1.0107×10^{10} TRF as the share of fossil fuels in the GEB (1.1472×10^{10} TRF) in 1990 (Akaev 2012, Table 2). The parameters r and ψ are derived by assuming a level of 95 % fossil fuels used for year 2020 and of 5 % for year

2160. They are $r = 0.05$ and $\psi = \psi_0 \left\{ 1 \big/ \left[1 - \alpha_\tau \tau_b \left(1 - f \right) \right] \right\}$, with $\psi_0 = 0.042$; $\alpha_\tau > 0$ here is a low-carbon technologies abatement efficiency parameter, chosen such that for the path corresponding to $\tau_b = 0.075$, carbon emissions reduction from baseline is about 50 % by year 2050; see Subsection (3.5.1) for details. The parameter f represents the share of investment in CCS (see Equation 19 below); the investment in low-carbon technologies is $1 - f$. Calculations based on Equation (13) using these values indicate that the share of fossil fuels will be significant throughout the whole twenty-first century and, when $\tau_b = 0$, this share decreases to 35 % only by its end (Akaev 2012).

As different types of fossil fuels produce different volumes of CO_2 in combustion, the dynamics of fossil fuel consumption – i.e., the relative shares of coal, oil, and natural gas – should be taken into account when calculating the future dynamics of CO_2 emission. Since these shares are not known at this time, the thesis assumes a logistic function for describing a reduction of the carbon intensity of energy c_c, in tons of carbon/tons of reference fuel ($tCTRF^{-1}$), throughout the 21st century (Akaev 2012),

$$c_c = c_{-\infty} + \frac{a_c}{1 + r \exp\left(-\psi t \right)}, \tag{14}$$

with $a_c > 0$ a constant.

Thus the carbon intensity σ, which is technology-dependent and represents the trend in the CO_2-output ratio, can now be given by the product of the energy intensity e_c in Equation (13) and the carbon intensity of energy c_c in Equation (14), thus:

$$\sigma = f_c \left[1 - \frac{r \exp\left(\psi t \right)}{1 + r\left(\exp\left(\psi t \right) - 1 \right)} \right] \left[c_{-\infty} + \frac{a_c}{1 + r \exp\left(-\psi t \right)} \right]. \tag{15}$$

The thesis can now calculate the de-carbonization of the economy, i.e. the declining growth rate of σ, by taking the natural logarithms of Equation (15) and getting the derivative with respect to time:

$$g_{\sigma} = \frac{f_{c}}{e_{c}}\left[\frac{\left[\psi r \exp(\psi t)\right]\left[1+r\left(\exp(\psi t)-1\right)\right]-\left[\psi r^{2}\exp(\psi t)\right]}{\left[1+r\left(\exp(\psi t)-1\right)\right]^{2}}\right]+\frac{1}{c_{c}}\left[\frac{a_{c}\psi r \exp(-\psi t)}{\left[1+r\exp(-\psi t)\right]^{2}}\right]. \qquad (16)$$

In a similar way as Equation (16) was derived from (15), the growth rate g_{Y} of per capita output is obtained from Equation (3) as

$$\frac{1}{Y}\frac{\mathrm{d}Y}{\mathrm{d}t} = \frac{\alpha}{K}\frac{\mathrm{d}K}{\mathrm{d}t} + \frac{(1-\alpha)}{H}\frac{\mathrm{d}H}{\mathrm{d}t} + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t},$$

or,

$$g_{Y} = \alpha g_{K} + (1-\alpha) g_{H} + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t}, \qquad (17)$$

with g_{K} the per capita physical capital growth and g_{H} the per capita human capital growth.

Human population evolves; cf. Golosovsky (2010), as

$$\frac{\mathrm{d}L}{\mathrm{d}t} = nL\left\{1-\exp\left[-\left(L/L(1990)\right)\right]\right\}, \qquad (18)$$

where n is the population growth rate as given in Equation (8). Equation (18) yields $L = 9\times10^{9}$ people in the year $t = 2100$. This value is consistent with the 2100 population projections of scenarios in the literature (e.g., van Vuuren et al. 2012, Table 3).

3.3.1 Inclusion of CCS in the industrial CO_2 emissions equation

In order to express the term g_{ccs} in Equation (12), the thesis assumes the leakage of captured carbon to be zero and use Akaev’s (2012) formula to define the reduction of emissions by the CCS as a fraction κ_{ccs}:

$$\kappa_{ccs} = \frac{2\exp(-\omega t)}{1+\exp(-\omega t)}, \tag{19}$$

In this equation, $\omega = \omega_0 \left\{1 - \left[1/\left(1+\alpha_\omega \tau_b f\right)\right]\right\}$, with ω_0 and α_ω constant, and the parameter f, as mentioned above, represents the share of investment in CCS; the investment in low-carbon technologies therefore is $1-f$ and appears in the energy intensity parameter ψ in Equation 13. Taking the natural logarithms and differentiating both sides of Equation (19), we get the growth rate of κ_{ccs} as

$$g_{\mathrm{ccs}} = \frac{(-\omega)}{\left[1+\exp(-\omega t)\right]}. \tag{20}$$

3.3.2 Cost of CCS

There is uncertainty regarding the costs of carbon capture, transportation and storage (Al-Juaied and Whitmore 2009; IPCC 2005, p. 354; Kalkuhl et al. 2014; Morita et al. 2000, 2001). The total cost of abating carbon through CCS is subject to research: very diverse estimates have been reported in the recent literature. These estimates span the wide range given by USD71–615 $(\mathrm{tC})^{-1}$ by the year 2100 (Al-Fattah et al. 2011, p. 296; Al-Juaied and Whitmore 2009; Bosetti 2010, p. 344; IEA 2004; IPCC 2005, 2014; Johnson and Keith 2004; Kalkuhl et al. 2014; McFarland et al. 2004; Metz 2010, p. 141; Middleton and Brandt 2013; Stephenson 2013, p. 132; van Vuuren et al. 2006, p. 271, Table F.1; Wise and Dooley 2004); here and elsewhere, we use dollar amounts normalized as USD_{1990}.

The estimated CO_2 emissions reduction due to CCS for the time interval 2020–2050 is 0.0038–0.7 GtCyr^{-1} (Bosetti 2010, p. 344; Galiana and Green 2010; IPCC 2005). Metz (2010, p. 216), on the other hand, projected the 2030 CCS reduction potential of CO_2 emissions at 0.0273–

0.0545 GtCyr^{-1} with a possibility of growing to 0.1364–0.409 GtCyr^{-1} by 2050; also see, Uyterlinde et al. (2006).

Keeping in mind this range of emissions reduction and of prices, we calibrated the parameter α_ω in that affects ω in Equation (19) above, in order to obtain similar values. For $\alpha_\omega = 46.1$, the scenario (see Subsection 4.4 below) corresponding to the abatement share $\tau_b = 0.075$ and with $f = 1.0$, gives aggregate carbon emissions reduction from baseline of 0.4 GtCyr^{-1} by 2050 and 0.17 GtCyr^{-1} by 2100. This emissions reduction comes at an approximate aggregate cost of USD124 (tC)$^{-1}$ by 2050 and USD558 (tC)$^{-1}$ by 2100. The cost is computed as $fG_E L = f\tau_b \tau YL$, i.e. the product of the share of investment in CCS (in this case $f = 1$) and the aggregate abatement costs; see Equation (5) and Equation (18) above. These costs lie within the range of the CCS costs in the literature, as given above. Given the large incertitude in this range of costs, we conduct in Subsection 5.3 below a sensitivity study to changes in the α_w value.

3.3.3 Damage function

The diomensionless damage function D gives the decline in Y, the global GDP, which results from an increase of the temperature T above the pre-industrial temperature $\hat{T}$. Nordhaus (1994a) formulates it as

$$D\left(T-\hat{T}\right)=\left[1+m_1\left(T-\hat{T}\right)^{\chi}\right]^{-1}, \tag{21}$$

with $m_1 > 0$ and $\chi > 0$, and the damage is defined as $Y - DY = \left(1-D\right)Y$. The greater $T-\hat{T}$, the smaller the value of $0 < D\left(T-\hat{T}\right) \le 1$, and accordingly the smaller the value DY of the remaining GDP, after the damage.

The representation of climate change damages is both a key part and one of the weakest points of IAMs (Tol and Fankhauser 1998). Temperature was used originally by Nordhaus (1994a) as a proxy for overall climate change. This may have taken the research community's focus off from potentially dangerous changes in climate apart from temperature (Toth 1995). However, without using a detailed climate model, temperature remains the best option available. This thesis assumes, in choosing this option, that physical and human capitals are distributed across infinitely many areas in the economy, and that the damages by natural disasters are uncorrelated across areas. With such an assumption, some version of the law of large numbers can justify a result like Equation (21) above; see Dell et al. (2014) for an insightful discussion about the damage function.

Nordhaus (1994a) first estimated the damage from CO_2 doubling – which, in his calculations was equivalent to a 3 ^{0}C warming – to be 1.33 % of global GDP (Nordhaus 1992). Additionally, he argued that damage would increase sharply as temperature increases; hence he used a quadratic function, in which $\chi = 2$, and m_1 is chosen to have 1.33 % loss of GDP for a 3 ^{0}C warming.

Roughgarden and Schneider (1999), using the same functional form (Equation 21), derived damage functions for each of the disciplines represented in an expert opinion solicited by a climate change survey. Taking an average of their values, this thesis gets $m_1 = 0.0067$; see, for instance, Table 1 in Labriet and Loulou (2003). On the other hand, the nonlinearity parameter $\chi = 2.43$ is calibrated in this thesis, so that the model's BAU emissions of CO_2 yr^{-1} and concentrations as well as change in global mean SAT from the pre-industrial level by 2100 mimic the Representative Concentration Pathway (RCP) 8.5. In fact, the projected climate change damages before and after abatement, as given by the damage function D in Equation (21), are consistent with the damages projected in Stern (2007); see also Creedy and Guest (2008) as well as Chen et al. (2012, p. 5).

3.4 Inclusion of a Biosphere module: CO_2-biomass interactions

Uzawa (1991, 2003) extended the analysis of the CO_2 cycle by including forests, represented by a state variable B (biomass). Biomass absorbs CO_2, so that an additional carbon sink appears in Eq. 1*d*. Thus, the forest acreage augments the absorption of CO_2 from the atmosphere. The only function of the stock of biomass in Uzawa's work was to sequester CO_2 and its stock could only be increased by net forestation activities, which use constrained resources. We did include here, though, the benefits of CO_2 fertilization, as suggested by Rosenberg (1991) in his commentary to Uzawa's (1991) paper.

In order to include fertilization effects in the Uzawa model, van Wassenhove (2000) proposed a model of the interaction between biomass and CO_2 that is an adaptation of the Lotka–Volterra predator–prey model (Lotka 1925; Volterra 1931). Including fertilization effects and deforestation, our system of equations for this adaptation is:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = g_{\mathrm{b}} B\left(1 - \frac{B}{\Lambda_{\mathrm{b}}}\right) + \gamma_{\mathrm{b}} B\left(C - \hat{C}\right) - \mathrm{d}_{for}, \tag{22}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2\left[E_{\mathrm{Y}} + E_{\mathrm{B}}\right] - \mu_{\mathrm{o}}\left(C - \hat{C}\right) - \gamma_{\mathrm{b}} B\left(C - \hat{C}\right), \tag{23}$$

where C is the CO_2 concentration in the atmosphere, B is the terrestrial photosynthetic biomass, Λ_{b} is biomass carrying capacity, g_{b} is the intrinsic colonization rate, γ_{b} is the fertilization parameter. The term d_{for} stands for deforestation efforts and E_{B} denotes emissions from deforestation, both these are defined in the next subsection. Here E_{Y} is industrial emissions as in Equation (12), and $\hat{C}$ the pre-industrial CO_2.

Equation (23) is not different from Equation (2), apart from the addition of the fertilization term. In this case, the "excess" CO_2 is absorbed into the ocean (second term on the right-hand side of Equation 23) but also into the terrestrial biomass (third term on the right-hand side of Equation

23). Biomass change and CO_2 sequestration – via photosynthesis – is represented by the logistic Equation 22 described by Clark (1990) as a population growth model.

3.4.1 *Carbon flux from deforestation and deforestation control*

This section follows the work of Eriksson (2013) who investigated the role of the forest in an IAM of the climate and the economy. In that work, deforestation does not change the growth rate but leads to a smaller stock of biomass — which is subject to that growth — as well as to a smaller carrying capacity, i.e., a smaller area where forest can potentially re-grow.

Deforestation is formulated in terms of forest biomass volume and not in terms of land area. The maximum forest biomass carrying capacity is modeled to decrease with deforestation as follows:

$$\frac{\mathrm{d}\Lambda_{\mathrm{b}}}{\mathrm{d}t} = -\frac{\Lambda_{\mathrm{b}}}{B} d_{for}, \tag{24}$$

where d_{for} is deforestation effort as in Equation (22), while the fraction Λ_{b}/B is a rescaling to convert biomass deforestation into biomass carrying capacity.

Deforestation is considered exogenous; we model it in our CoCEB model in agreement with Nordhaus and Boyer (2000), who prescribed carbon emissions from deforestation to decrease in time according to:

$$E_{\mathrm{B}} = \left[E_{\mathrm{B0}} \exp\left(-\delta_{\mathrm{b}} t\right)\right]\left(1 - R_{\mathrm{d}}\right), \tag{25}$$

where the parameter E_{B0} represents carbon emission in the first time period, δ_{b} is the rate of decline of land-use emissions, and $R_{\mathrm{d}} \geq 0$ is the deforestation control rate. These emissions can be converted into biomass deforestation by means of a global carbon intensity parameter θ_{for} (Eriksson 2013; see also FAO 2010). The carbon intensity parameter, in this case, represents the average amount of carbon per volume of growing forest biomass. The total biomass deforestation in GtC at any time period is then given by

$$d_{for} = \left[\frac{E_{\mathrm{B0}}}{\theta_{for}} \exp\left(-\delta_{\mathrm{b}} t\right) \right] \left(1 - R_{\mathrm{d}}\right). \tag{26}$$

When $R_{\mathrm{d}} = 0$, we have the baseline deforestation. The deforestation control rate can either reduce or increase deforestation. When net deforestation is prevailing, $d_{\mathrm{for}} > 0$ or $0 \le R_{\mathrm{d}} < 1$, and when net afforestation or reforestation is prevailing, $d_{\mathrm{for}} < 0$ or $R_{\mathrm{d}} > 1$.

The total carbon emissions are hence assumed here to be the sum of industrial fossil fuel use emissions E_{Y} from Equation (12) and of deforestation emissions E_{B} from Equation (25).

3.4.2 Cost of the deforestation activity

The rental cost — that is, the rental payment to the landowner to hinder conversion of forested land — of avoiding direct release of carbon in one time period is given by the marginal cost function (Eriksson 2013; Kindermann et al. 2008):

$$\bar{V}_{\mathrm{mc}} = \pi_1 \left(R_{\mathrm{e}}\right)^{\pi_2} + \left[\left(\pi_3 + \pi_4 t\right)^{\left(\pi_5 R_{\mathrm{e}}\right)} - 1 \right], \tag{27}$$

where the π’s are the estimated cost parameters and R_e is the reduction of direct carbon emission from deforestation. From Equation (25) this is given by

$$R_{\mathrm{e}} = \left(E_{\mathrm{B0}} \exp\left(-\delta_{\mathrm{b}} t\right)\right) R_{\mathrm{d}}. \tag{28}$$

The marginal cost or R_{d} increases with the level of reduction of carbon emission due to deforestation. The land under forest is assumed to carry primarily a low opportunity cost. As more land under forest is targeted for deforestation control, its opportunity cost and hence its marginal cost increases over time. This is due to the fact that as the deforestation level declines, the land under forest that remains carries a high opportunity cost.

The total cost of avoiding deforestation which can be written as

$$\frac{\mathrm{d}\bar{V}}{\mathrm{d}t} = \int_{t} \bar{V}_{\mathrm{mc}}\left(s\right) ds . \tag{29}$$

Rental payment occurs each time period and land under forest saved from conversion will not be deforested in future time periods. The thesis assumes forested land conversion, for example to agricultural land, as an investment in the primary input land, viewing land in the capital stock as a representative for the capital value of land devoted to production of non-forest goods.

The capital stock is hence assumed to grow with investment in land, i.e., conversion of land to agricultural land and urbanization or infrastructure. Deforestation is mainly caused by these two types of conversions, and hence the capital stock increases with deforestation. The accumulated investment in land is here assumed to be implicit in the total capital stock and does not affect the development of the total capital stock when following the baseline deforestation pattern. Reducing the baseline deforestation is here equivalent to a disinvestment of land capital resulting in a smaller net investment in the total capital stock. The per capita cost of avoiding deforestation is thus $V = \bar{V}/L$.

Through a meta-analysis of published works, Phan et al. (2014) estimated the cost of carbon emissions reduction due to deforestation control to range from 0.11 to USD246 $(\mathrm{tC})^{-1}$ with a mean of USD19 $(\mathrm{tC})^{-1}$. Actually, Kindermann et al. (2008) used three economic models of global land use and management — Global Timber Model (GTM), Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA), and Generalized Comprehensive Mitigation Assessment Process Model (GCOMAP) — to analyze the economic potential contribution of deforestation control activities to reduced GHG emissions. The latter authors found out that a 10 % deforestation control could be feasible within the context of current financial flows.

Following the latter result, we take $R_{\mathrm{d}} = 0.1$ as the standard value in this thesis, but will test the robustness of our results by also using other R_{d}-values. In the CoCEB model, with 100 %

investment in low-carbon technologies and with $\tau_b = 0.075$, the value of $R_d = 0.1$ gives an approximate aggregate cost of deforestation emissions reduced of USD164 $(tC)^{-1}$ by 2100. We notice that the CoCEB total cost for $R_d = 0.1$ is within the range of deforestation control costs given by Phan et al. (2014).

Finally, including the biosphere module and deforestation control, the evolution of total per capita capital accumulation K in Eq. 9 can be written as

$$\frac{dK}{dt} = AK^{\alpha}H^{1-\alpha}D\left(T - \hat{T}\right)\left[1 - \tau(1+\tau_b) - c(1-\tau)\right] - \left(\delta_K + n\right)K - V \,. \tag{30}$$

Given the large incertitude of the estimated cost of deforestation control, a sensitivity analysis to the values of the parameters in Equation (27) is performed in Subsection 5.4 below.

3.5 Climate change abatement measures

A key part of the mitigation literature concentrates on the feasibility of different climate targets, often defined by GHG concentrations or by radiative forcing levels, and the associated costs; see van Vuuren et al. (2012) and the citations therein. The broad range of options available for mitigating climate change includes the reduction of CO_2 emissions (increasing energy efficiency, increasing non-fossil fuel-based energy production, and the use of CCS), and CO_2 removal (Edenhofer et al. 2012; Steckel et al. 2013).

3.5.1 Abatement policies

For reasons of political feasibility as well as of efficiency, the focus of climate policy has been on energy intensity and carbon intensity of energy, and not on population and wealth (Tol 2010). All the popular policies point to increased de-carbonization efforts, i.e., to an increase in g_{σ}. The historical record, however, shows quite clearly that global and regional rate of de-carbonization have seen no acceleration during the recent decade and in some cases even show evidence of re-carbonization (Canadell et al. 2007; Prins et al. 2009).

Among the various market-based (or economic) instruments adopted to reduce CO_2 emissions, *carbon taxes* and *tradable permits* are the most widely discussed *cost-efficient* policies, both at a national and international level (Fiddaman 1997; Fischer et al. 2003; IPCC 2007c; Mankiw 2007; Nordhaus 2008; Pizer 1999, 2002, 2006; Uzawa 2003; Weitzman 1974). *Forestry policies*, particularly reduced deforestation, also emerge as additional low cost measures for the reduction of CO_2 emissions. Reduced deforestation would cut CO_2 emissions and increased afforestation would sequester CO_2 from the atmosphere (see, e.g., Bosetti et al. 2011; Rose et al. 2012; Tavoni et al. 2007; Wise et al. 2009).

3.5.2 Abatement share

The abatement costs of several IAMs tend to cluster in the range of about 1–2 % of GDP as the cost of cutting carbon emissions from baseline by 50 % in the period 2025–2050, and about 2.5–3.5 % of GDP as the cost of reducing emissions from baseline by about 70 % by 2075–2100 (Boero et al. 1991; Boero 1995; Clarke et al. 1996; Cline 1992, p. 184; Tol 2010, p. 87, Figure 2.2) with an increasing dispersion of results as higher emission reduction targets are set (Boero et al. 1991).

Using the definition of abatement in Equation (5) and the GDP evolution in Equation (3), the thesis obtains an abatement share that gives an abatement cost equivalent to 1 % of GDP by 2050 to be

$$\frac{G_{\mathrm{E}}}{Y} = \tau_{\mathrm{b}}\tau = 0.01 \Rightarrow \tau_{\mathrm{b}} = 0.05 . \qquad (31)$$

Similarly, the abatement share giving an abatement cost equivalent to 2 % of GDP by 2050 is $\tau_b = 0.1$. The thesis takes, as the lower abatement share, the average $\tau_b = 0.075$ of the two abatement shares that give an abatement cost equivalent to 1.5 % of GDP by 2050.

Next, the thesis chooses the low-carbon technologies abatement efficiency parameter $\alpha_\tau = 1.8$ such that, for the path corresponding to $\tau_b = 0.075$, carbon emissions reduction from baseline is about 50 % by 2050. The scenario corresponding to $\tau_b = 0.075$ also happens to mimic the RCP6.0 by 2100 (IPCC 2013; Fujino et al. 2006; Hijioka et al. 2008). For the other non-BAU scenarios, the thesis chooses abatement shares of $\tau_b = 0.11$ and 0.145, such that an emissions reduction of 50 % or more from baseline by 2050 and beyond gives a reduction in GDP of 2.2 % and 2.9 %, respectively; the scenario given by $\tau_b = 0.11$ also mimics RCP4.5 (IPCC 2013; Clerke et al. 2007; Wise et al. 2009). Note that the abatement shares in Greiner (2004) and Greiner and Semmler (2008), which use Equation (11), are about 10 times lower than the ones chosen here.

3.5.3 Deforestation control and afforestation

Forestry – including afforestation (the planting of trees on land where they have not recently existed), reforestation, avoided deforestation (Rose et al. 2012; Wise et al. 2009), and forest management – can lead to increased sequestration of atmospheric CO_2 and has therefore been proposed as a strategy to mitigate climate change (Anderson et al. 2011; Canadell and Raupach 2008; IPCC 2000; Pacala and Socolow 2004). Under the Kyoto Protocol, the so-called flexible mechanisms have been established to combat GHGs cost-effectively. One of these mechanisms, the CDM, allows governments and business organizations from industrialized countries to invest in forestry in developing countries to accrue carbon credits to offset industrialized emissions. There are parallel negotiations underway on the development of policies for Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) – a voluntary scheme to mitigate land carbon emissions from developing countries. Overall, there is strong interest in the role of forestry in climate mitigation agreements and legislation (Schlamadinger and Bird 2007).

To be effective in mitigating climate change, forests need to sequester carbon or allow for reduced fossil–fuel burning through bioenergy production, while avoiding biophysical effects that would jeopardize the net climate benefits and long-term sustainability (Anderson et al. 2011). This thesis has incorporated deforestation control into the model framework.

3.6 Summary: CoCEB, the Coupled Climate–Economy–Biosphere model

The coupled CoCEB model is described by Equations (1), (10), (12), (22), (23), and (30). The model describes the temporal dynamics of six variables: per capita physical capital K, per capita human capital H, the average global surface air temperature T, the CO_2 concentration in the atmosphere C, biomass B, and industrial CO_2 emissions E_{Y}.These six main variables are governed by a set of nonlinear, coupled ordinary differential equations (ODEs); they are complemented by a number of auxiliary variables, which are connected to them by ODEs and algebraic equations.

The equations are grouped for the reader’s convenience below:

$$
\begin{aligned}
\frac{\mathrm{d}K}{\mathrm{d}t} &= \mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\left[1-\tau(1+\tau_{\mathrm{b}})-c(1-\tau)\right]-\left(\delta_{\mathrm{K}}+n\right)K-V, && (32a)\\
\frac{\mathrm{d}H}{\mathrm{d}t} &= \varphi\left\{\mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\left[1-\tau(1+\tau_{\mathrm{b}})-c(1-\tau)\right]\right\}-\left(\delta_{\mathrm{H}}+n\right)H, && (32b)\\
\frac{\mathrm{d}T}{\mathrm{d}t} &= \frac{\left[1-\alpha_{\mathrm{T}}\right]\mathrm{Q}}{4c_{\mathrm{h}}}-\frac{\varepsilon\tau_{\mathrm{a}}\sigma_{\mathrm{T}}}{c_{\mathrm{h}}}T^{4}+\frac{6.3\beta_{1}\left(1-\xi\right)}{c_{\mathrm{h}}}\mathrm{In}\left(\frac{C}{\hat{C}}\right), && (32c)\\
\frac{\mathrm{d}C}{\mathrm{d}t} &= \beta_{2}\left[E_{\mathrm{Y}}+E_{B}\right]-\mu_{\mathrm{o}}\left(C-\hat{C}\right)-\gamma_{\mathrm{b}}B\left[C-\hat{C}\right], && (32d)\\
\frac{\mathrm{d}B}{\mathrm{d}t} &= g_{\mathrm{b}}B\left(1-\frac{B}{\Lambda_{\mathrm{b}}}\right)+\gamma_{\mathrm{b}}B\left[C-\hat{C}\right]-\mathrm{d}_{for}, && (32e)\\
\frac{\mathrm{d}E_{\mathrm{Y}}}{\mathrm{d}t} &= \left[g_{\sigma}+g_{\mathrm{Y}}+n+g_{\mathrm{ccs}}\right]E_{\mathrm{Y}}. && (32f)
\end{aligned}
$$

The parameter values used in the model are as described in the text above and in Table 1 below. They have been chosen according to standard tables and previous studies.

Table 1 List of variables and parameters and their values used

Symbol	Meaning	Value	Units	Source
INDEPENDENT VARIABLES				
K	Per capita physical capital		Trillions USD_{1990}	
H	Per capita human capital		Trillions USD_{1990}	
T	Average global surface temperatures		Kelvin (K)	
C	Atmospheric CO_2 concentration		GtC	
B	Biomass		GtC	
E_{Y}	Industrial CO_2 emissions		GtCyr^{-1}	
INITIAL (1990) VALUES FOR INDEPENDENT VARIABLES				
k_0	Per capita physical capital-human capital ratio K_0/H_0	8.1	Ratio	Erk et al. (1998)
K_0		0.8344	$\text{USD}_{1990}\,10^4$	Nordhaus and Boyer (2000)
H_0		0.1039	$\text{USD}_{1990}\,10^4$	K_0/k_0
T_0		287.77	Kelvin (K)	
C_0		735	GtC	Nordhaus and Boyer (2000)
B_0		500	GtC	van Wassenhove (2000)

E_{Y0}		6	$GtCyr^{-1}$	Lenton (2000)

PARAMETERS AND OTHER SYMBOLS

ECONOMY MODULE

n	Population growth rate		$\%yr^{-1}$	Nordhaus (2013a)
L	Human population		Millions	
L_0	1990 world population	5632.7	Millions	Nordhaus and Boyer (2000)
n_0	1990 population growth rate	1.57	$\%yr^{-1}$	Nordhaus and Boyer (2000)
Λ_L	Population carrying capacity	11360	Millions	Aral (2013)
A	Total factor productivity	2.9		Greiner and Semmler (2008)
c	Consumption share	80	$\%yr^{-1}$	Greiner and Semmler (2008)
φ	External effect coefficient	0.1235		
δ_K	Depreciation rate of K	7.5	$\%yr^{-1}$	Greiner and Semmler (2008)
δ_H	Depreciation rate of H	7.2	$\%yr^{-1}$	
δ_n	Decline rate of n	2.22	$\%yr^{-1}$	Nordhaus and Boyer (2000)
α	Capital share	0.35		Gollin (2002)
τ	Tax rate	20	$\%yr^{-1}$	Greiner and Semmler (2008)
τ_b	Abatement share	0;0.075;0.11; 0.145	Ratio	

DAMAGE FUNCTION

m_1		0.0067		Roughgarden and Schneider (1999)
χ		2.43		

CLIMATE MODULE (CARBON CYCLE & SURFACE AIR TEMPERATURE)

β_2	Part of CO_2 emissions taken up by oceans and do not enter the atmosphere	0.49		IPCC (2001a, p. 39)
μ_o	Rate of CO_2 absorption from the atmosphere into the ocean	0.0083		Nordhaus (1994a)
$\hat{C}$	Pre-industrial CO_2 concentration	596.4	GtC	Wigley (1991)
e_c	Energy intensity		$TRF/USD10^3$ of $\bar{Y}$	Akaev (2012)
c_c	Carbon intensity of energy		$Tctrf^{-1}$	Akaev (2012)
g_{ec}	Growth rate of e_c			
g_{cc}	Growth rate of c_c			
σ	Carbon intensity		$tC/USD10^3$ of $\bar{Y}$ (Ratio)	Nordhaus and Boyer (2000)

g_σ	Rate of decline of σ			
σ_0	1990 level σ	0.274	tC/USD10^3 of $\bar{Y}$ (Ratio)	Nordhaus and Boyer (2000)
ψ_0		0.042		Akaev (2012)
α_τ	Low-carbon technologies abatement efficiency	1.8		
r		0.05		Akaev (2012)
$c_{-\infty}$	c_c used before 1990	0.1671	$tCTRF^{-1}$	
a_c		0.169		Akaev (2012)
c_h	Earth specific heat capacity	16.7	$Wm^{-2}K^{-1}$	Schwartz (2008)
α_T	Planetary/Surface albedo	0.3		McGuffie and Henderson-Sellers (2005)
ε	Emissivity	0.95		McGuffie and Henderson-Sellers (2005)
σ_T	Stefan-Boltzmann constant	$5.67 \text{x} 10^{-8}$	$Wm^{-2}K^{-4}$	McGuffie and Henderson-Sellers (2005)
τ_a	Infrared transmissivity	0.6526		McGuffie and Henderson-Sellers (2005)
Q	Solar flux	1366	Wm^{-2}	Gueymard (2004)
ξ	T rise absorbed by the oceans	0.23		Greiner and Semmler (2008)
β_1	Feedback effect	3.3		Greiner and Semmler (2008)
$\hat{T}$	Pre-industrial T	287.17	K	

CCS

κ_{ccs}	CCS technologies		Ratio	Akaev (2012)
g_{ccs}	Growth rate of κ_{ccs}			
ω_0		0.01		Akaev (2012)
α_ω	CCS technologies abatement efficiency	46.1		
f	Share of investment in CCS		$\%yr^{-1}$	

BIOSPHERE MODULE (BIOMASS)

Λ_b	Biomass carrying capacity		GtC	Eriksson (2013)
Λ_{b0}	1990 biomass carrying capacity	900	GtC	van Wassenhove (2000)
E_{B0}	1990 land-use emissions	1.128	$GtCyr^{-1}$	Nordhaus and Boyer (2000)
γ_b	Fertilization parameter	0.0000053	$(GtC)^{-1}$	van Wassenhove

				(2000)
g_b	1990 biomass intrinsic growth rate	4	$\%yr^{-1}$	van Wassenhove (2000)
δ_b	Rate of decline of land-use emissions	0.01		Nordhaus and Boyer (2000)
θ_{for}	Mean carbon intensity in global forest biomass	0.5147	GtC	Eriksson (2013)
R_d	Deforestation control rate	0.1		Kindermann et al. (2008)
π_1; π_2; π_3; π_4; π_5	Deforestation control cost	14.46;0.26; 1.022; 0.03; 20		Eriksson (2013)

CHAPTER 4

NUMERICAL SIMULATIONS AND ABATEMENT RESULTS

4.1 Experimental design

In the following, the thesis confined the investigations to the transition path for the 110 years from the baseline year 1990 to the end of this century. The thesis studied the abatement share and how investment in clean technologies effected industrial carbon emissions. The effect of including biomass and deforestation control as well as CCS technologies into the model was also analyzed. The goal was to understand how the different mitigation measures compare and which was more effective.

Table 2 The scenarios studied herein

Scenario		Control
i)	Run with no investment in low-carbon technologies, no biomass and no CCS: first (old) BAU	$\tau_b = 0$; $f = 0$; $B = 0$; $R_d = 0$
ii)	3 Runs with investment in low-carbon technologies, no biomass and no CCS	$\tau_b = 0.075, 0.11, 0.145$; $f = 0$; $B = 0$; $R_d = 0$
iii)	Run with biomass, no CCS and no deforestation control: second (new) BAU	$\tau_b = 0$; $f = 0$; $B \neq 0$; $R_d = 0$
iv)	12 Runs with investment in CCS	$f = 0, 0.3, 0.6, 1.0$; $\tau_b = 0.075, 0.11, 0.145$; $R_d = 0$
v)	20 Runs with deforestation control	$R_d = 0, 0.1, 0.5, 1, 1.2$; $\tau_b = 0, 0.075, 0.11, 0.145$; $f = 0$

The scenarios studied herein are summarized in Table 2. We perform 37 integrations with an aggregate CO_2 concentration larger than or equal to the pre-industrial level:

i) The first is a control or BAU integration, with no abatement activities, i.e., $\tau_{\mathrm{b}} = 0$ and no biomass, CCS or deforestation control;

ii) Next, three integrations with abatement measures, corresponding to τ_{b} = 0.075, 0.11 and 0.145, as chosen in Subsection 3.5.2 again with no biomass, CCS or deforestation control;

iii) The third is again a control integration, with biomass evolution included but no CCS and no deforestation control. This is equivalent to a BAU simulation in the IPCC terminology, but not the same as the BAU in i) above. The difference lies in the presence of interactive biomass that exchanges carbon with the atmosphere;

iv) Then we perform 12 integrations using CCS investments but no deforestation control, $R_{\mathrm{d}} = 0$. The 12 runs correspond to a matrix of four values of the share f of investment in CCS, f = 0, 0.3, 0.6, and 1.0, times three values of total abatement share τ_{b}, τ_{b} = 0.075, 0.11, and 0.145;

v) Last, 20 integrations with inclusion of deforestation control are performed; they correspond to a matrix of five values each of R_{d} = 0, 0.1, 0.5, 1.0, and 1.2, times four values of τ_{b} = 0, 0.075, 0.11, 0.145, with f = 0.

The CoCEB model is integrated in time starting from the initial values at year 1990, as listed in Table 1. The damage function exponent χ in Equation (21) is taken to be super-quadratic, $\chi = 2.43$; all other parameter values are as in Table 1. The time step is 1 year and the integrations are stopped at year 2100. The values of CO_2 emissions and concentration, biomass, temperature, damage and GDP growth at the end of the integrations (year 2100) are shown in Tables 3, 6, 7, and 8, respectively, for the low-carbon runs, the BAU runs, the CCS runs, and the deforestation control runs.

4.2 Integrations without and with investment in low-carbon technologies and with no CCS, biomass or deforestation control

From Table 3, it is clear that, if no action is taken to reduce baseline industrial CO_2 emissions, these will attain 29.3 $GtC\,yr^{-1}$ by 2100, leading to an atmospheric CO_2 concentration of 1842 GtC, i.e. about 3.1 times the pre-industrial level at that time.

Table 3 Variables values for year 2100 for the model without and with investment in low-carbon technologies: scenarios i) and ii) in Table 2, with $\chi = 2.43$

τ_b	Emissions E_Y ($GtC\,yr^{-1}$)	CO_2 $C/\hat{C}$	Deviation from pre-industrial $T-\hat{T}$ (^0C)	Damages (% GDP)	GDP growth g_Y (%yr^{-1})
0	29.3	3.1	5.2	26.9	1.1
0.075	11.8	2.1	3.4	11.6	2.1
0.11	5.9	1.7	2.6	6.6	2.2
0.145	2.5	1.5	2.0	3.5	2.0

As a consequence, global average SAT will rise by 5.2 ^0C from the pre-industrial level with a corresponding damage to the per capita GDP of 26.9 %. This compares well with the IPCC results for their RCP8.5 scenario, cf. Table 5 below.

The year-2100 changes in our three non-BAU scenarios' global mean SAT from the pre-industrial level are 3.4, 2.6, and 2 ^0C. The RCP6.0, RCP4.5, and RCP2.6 give a similar range of change in global SAT of 1.4–3.1 ^0C with a mean of 2.2 ^0C, 1.1–2.6 ^0C with a mean of 1.8 ^0C, and 0.3–1.7 ^0C with a mean of 1 ^0C, respectively (IPCC 2013). We note that our scenarios' change in temperature compare well with the IPCC ones.

The cumulative CO_2 emissions for the 1990–2100 period in this thesis's non-BAU scenarios are 1231 GtC, 1037 GtC, and 904 GtC. On the other hand, for the 2012–2100 period, RCP6.0 gives cumulative CO_2 emissions in the range of 840–1250 GtC with a mean of 1060 GtC; RCP4.5 gives a range of 595–1005 GtC with a mean of 780 GtC, while RCP2.6 gives a range of 140–410 GtC with a mean of 270 GtC. The two former RCPs agree rather well with our results, while RCP2.6 is less pessimistic.

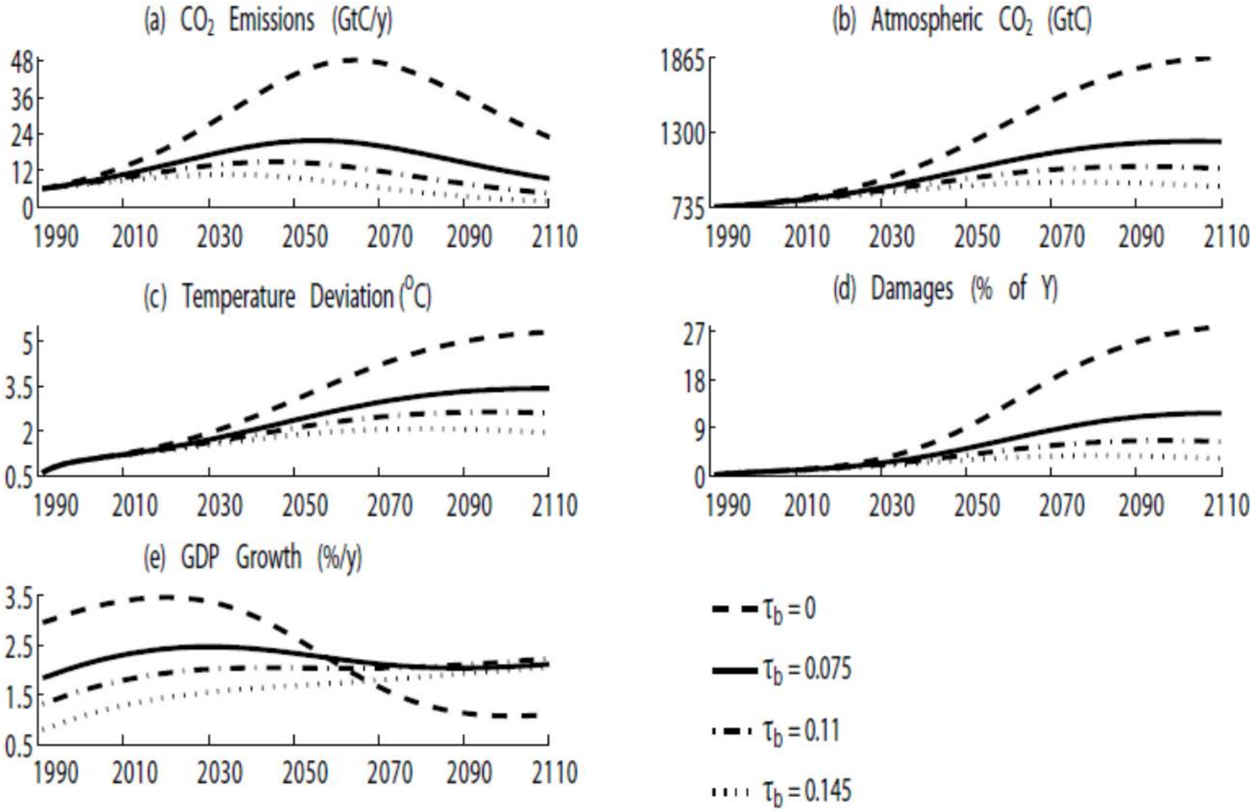

Fig. 3 Evolution of several CoCEB model variables in time, for abatement shares τ_b that range from 0.0 (no abatement) to 0.145; see legend for curves, with $\tau_b = 0$ — dashed, $\tau_b = 0.075$ — solid, $\tau_b = 0.11$ — dash-dotted, and $\tau_b = 0.145$— dotted

In Figure 3, the time-dependent evolution of the CoCEB output is shown, from 1990 to 2100. The figure shows that an increase in the abatement share τ_b from 0 to 0.145 leads to lower CO_2 emissions per year (Fig. 3a) as well as to lower atmospheric CO_2 concentrations (Fig. 3b) and, as a consequence, to a lower average global SAT (Fig. 3c), compared to the baseline value. This physical result reduces the economic damages (Fig. 3d) and hence the GDP growth decrease is strongly modified (Fig. 3e).

Figure 3e is the key result of this thesis: it shows that abatement policies do pay off in the long run. From the figure, it is seen that – because of mitigation costs – per capita GDP growth on the paths with nonzero abatement share, $\tau_{\mathrm{b}} \neq 0$, lies below growth on the BAU path for the earlier time period, approximately between 1990 and 2060. Later though, as the damages from climate change accumulate on the BAU path (Fig. 3d), GDP growth on the BAU slows and falls below the level on the other paths (Fig. 3e), i.e., the paths cross.

This crossing of the paths means that mitigation allows GDP growth to continue on its upward path in the long run, while carrying on BAU leads to great long-term losses. As will be shown in Table 3 below, the losses from mitigation in the near future are outweighed by the later gains in averted damage. The cross-over time after which abatement activities pay off occurs around year 2060; its exact timing depends on the definition of damage and on the efficiency of the modeled abatement measures in reducing emissions.

The average annual growth rates (AAGRs) of per capita GDP between 1990 and 2100, are given in our model by $\left(1/110\right)\sum_{t=1990}^{t=2100} g_Y\left(t\right)$ and their values, starting from the BAU scenario, are 2.6, 2.4, 2.1 %yr^{-1}, and 1.8 %yr^{-1}, respectively. Relative to 1990, these correspond to approximate per capita GDP increase of 5.5–14.5 times, that is USD 34×10^3–90×10^3 in year 2100, up from an approximate of USD 6×10^3 in 1990. Our scenarios' AAGRs and the 2100-to-1990 per capita GDP ratio agree well with scenarios from other studies, which give AAGRs of 0.4–2.7 %yr^{-1} and a per capita GDP increase of 3–21 fold, corresponding to USD 15×10^3–106×10^3 (Chakravorty et al. 1997; Grübler et al. 1999; Holtz-Eakin and Selden 1995; Krakauer 2014; Leggett et al. 1992; Nakićenović and Swart 2000; Nordhaus 2007; Rabl 1996; Schrattenholzer et al. 2005, p. 59; Stern 2007; van Vuuren et al. 2012).

It is worth noting here that there has been a raging debate on the choice of either the market exchange rates (MER) or the purchasing power parity (PPP) (see, e.g., Vachris and Thomas 1999) in expressing GDP growth rates. However, Manne et al. (2005), on posing the question as to whether, when projecting future temperature, it makes a difference if MER or PPP is used, found the answer to be yes, but with a minor difference. Their results suggested that the debate over the proper conversion factor for potential GDP may be decoupled from that over SAT change due to climate change.

Now, According to the United Nations Framework Convention on Climate Change (UNFCCC 1992), the average global SAT should not exceed its pre-industrial level by more than 2 ^{0}C. This SAT target means that global efforts to restrict or reduce CO_2 emissions must aim at an atmospheric CO_2 concentration of no more than 1171.5 GtC. This CO_2 target can be achieved if carbon emissions are reduced to no more than 3.3 GtCyr^{-1}, or nearly half relative to the 1990 level of 6 GtCyr^{-1} (Akaev 2012). This goal is met, in the highly simplified model, by the path with the highest abatement share of the four, $\tau_b = 0.145$. From Table 3 and Figure 3, it is noticed that this level of investment in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system enable emissions to decrease to 2.5 GtCyr^{-1} by year 2100 (Figure 3a), about a 58 % drop below the 1990 emissions level. This emissions drop enables the deviation from pre-industrial SAT to reach no higher than 2 ^{0}C by year 2100 (Figure 3c).

The per capita abatement costs $G_E = \tau_b X = \tau_b \tau Y$ from Equation (5) and the damage costs $(1-D)Y$ from Equation (21) for the various emission reduction paths are given in Table 4 for the year 2100.

Table 4 Per capita abatement costs and damage costs at year 2100, with $\chi = 2.43$

Abatement share τ_b	% emissions (E_Y) reduction from baseline	Per capita abatement costs (% Y)	Per capita damage costs (% Y)
0	0	0	26.9
0.075	60	1.5	11.6
0.11	80	2.2	6.6
0.145	92	2.9	3.5

From the table it is noticed that, generally, the more one invests in abatement, the more emissions are reduced relative to baseline and the less the cost of damages from climate change. From Tables 3 and 4, it is noticed that limiting global average SAT to about 2 ^{0}C over pre-industrial levels would require an emissions reduction of 92 % from baseline by 2100, at a per capita cost of USD990, which translates to 2.9 % of per capita GDP. Although attaining the 2 ^{0}C goal comes at a price, the damages will be lower all along and the GDP growth better than for BAU starting from the cross-over year 2058.

Recall, moreover, that the benefits of GHG abatement are not limited to the reduction of climate change costs alone. A reduction in CO_2 emissions will often also reduce other environmental problems related to the combustion of fossil fuels. The size of these so-called secondary benefits is site-dependent (IPCC 1996b, p. 183), and it is not taken into consideration as yet in the CoCEB model.

Table 5 Comparison between global results of alternative policies

Global industrial CO_2 emissions ($GtCyr^{-1}$)							
Policy Scenario	1995	2005	2010	2020	2030	2050	2100
CoCEB model: $\tau_b = 0$	7.1	10.8	13.2	19.3	27.0	43.4	29.3
CoCEB model : $\tau_b = 0.075$	6.8	9.2	10.6	13.8	17.0	21.6	11.8
CoCEB model : $\tau_b = 0.11$	6.7	8.6	9.6	11.7	13.5	14.7	5.9
RCP8.5 (Rao and Riahi 2006; Riahi et al. 2007)	-	8	8.9	11.5	13.8	20.2	28.7
RCP6.0 (Fujino et al. 2006; Hijioka et al. 2008)	-	8	8.5	9	10	13	13.8
RCP4.5 (Clerke et al. 2007; Smith and Wigley 2006; Wise et al. 2009)	-	8	8.6	9.9	11	11	4.2

Global atmospheric CO_2 concentration (GtC)							
	1995	2010	2020	2030	2050	2075	2100
CoCEB model: $\tau_b = 0$	743	793	852	939	1206	1612	1842
CoCEB model : $\tau_b = 0.075$	743	785	826	880	1014	1168	1231
CoCEB model : $\tau_b = 0.11$	743	781	816	858	948	1027	1037
RCP8.5 (Riahi et al. 2007)	-	829	886	956	1151	1529	1993
RCP6.0 (Fujino et al. 2006; Hijioka et al. 2008)	-	829	872	914	1017	1218	1427
RCP4.5 (Clerke et al. 2007; Wise et al. 2009)	-	829	875	927	1036	1124	1147

Table 5 gives a comparative summary of the CoCEB model’s results and those from other studies that used more detailed IAM models and specific IPCC (2013) RCPs. It is noticed that the CO_2 emissions per year and the concentrations in the transition path up to year 2100 agree fairly well with those of RCP8.5, RCP6.0 and RCP4.5.

4.3 Control integration: run with biomass, no CCS and no deforestation control (new BAU)

In Table 6, a summary of the behavior of the BAU integration with inclusion of the biomass is shown. The results of the BAU integration of Subsection 4.1 (reported in the 1st line of the table for comparison) and in the present Subsection's BAU are qualitatively similar, yet the new BAU has CO_2 emissions of 34 GtCyr^{-1} by year 2100. This is an increase of approximately 4.7 GtCyr^{-1} from the 29.3 GtCyr^{-1} of the BAU of Subsection 4.2. From our calculations (not shown) industrial CO_2 contributes to about 92 % of this increment, due to increased per capita GDP growth, while emissions from deforestation, which are declining over time, contribute about 8 %.

Table 6 Variable values for year 2100 for the model with no biomass (B = 0) and no CCS (f = 0), i.e. BAU of Table 3, and with no deforestation control but $B \neq 0$ (new BAU run)

Scenario	Emissions $E_Y + E_B$ (GtCyr^{-1})	CO_2 $C/\hat{C}$	Biomass B (GtC)	Deviation from pre-industrial $T - \hat{T}$ (^{0}C)	Damages (% GDP)	GDP growth g_Y (%yr^{-1})
$\tau_b = 0; B = 0\ R_d = 0$ (BAU of Subsection 4.2)	29.3	3.1	-	5.20	26.9	1.07
$\tau_b = 0; B \neq 0;\ R_d = 0;$ (BAU of Subsection 4.3)	34.0	2.9	810	4.93	24.5	1.42

There is no contradiction in the fact that these higher CO_2 emissions are accompanied by lower temperature increase. The increase of emissions is due to the appreciation in per capita GDP, in turn due to a decrease in atmospheric CO_2 through its sequestration owing to biomass fertilization and hence a decline in global surface air temperature (SAT) and consequently damages. Atmospheric CO_2 decreases from 1842 GtC to 1729 GtC, i.e., about 113 GtC by 2100, which implies a sequesteration of approximately 1 GtCyr^{-1} between 1990 and 2100.

The model's behavior in response to inclusion of biomass agrees with Mackey et al.'s (2013) claims that the capacity of terrestrial ecosystems to store carbon is finite and that the current sequestration potential primarily reflects depletion due to past land-use. Therefore, avoiding emissions from land carbon stocks and refilling depleted stocks reduces atmospheric CO_2 concentration, but the maximum amount of this reduction is equivalent to only a small fraction of potential fossil fuel emissions.

4.4 Using CCS methods but no deforestation control

The effects of including CCS into the model, via a fraction f of the total abatement share τ_b, are summarized in Table 7. Deforestation control is not implemented in these runs, $R_d = 0$. Note that the first column of Table 7 repeats for comparison the results of the new BAU run of Table 6; since $\tau_b = 0$ in this column, the same results are obviously obtained for all values of f.

On the other hand, when $f = 0$, i.e for the first row of Table 7, all the abatement share goes into investment in low-carbon technologies as in Subsection 4.2; varying the value of τ_b in this case, we obtain results that are qualitatively similar to those obtained in Subsection 4.2, although not exactly equal to them, due to the inclusion of the interactive biomass.

Table 7 Variable values for year 2100 with deforestation emissions in parentheses, for the runs with investment in CCS scenario

τ_b f		0	0.075	0.11	0.145
0	$E_Y + E_B$	34.0 (0.4)	13.3 (0.4)	6.7 (0.4)	3.0 (0.4)
	$T - \hat{T}$	4.93	3.12	2.37	1.78
	g_Y	1.42	2.30	2.32	2.08
0.3	$E_Y + E_B$	34.0 (0.4)	12.7 (0.4)	6.8 (0.4)	3.4 (0.4)
	$T - \hat{T}$	4.93	2.99	2.30	1.78
	g_Y	1.42	2.39	2.35	2.08
0.6	$E_Y + E_B$	34.0 (0.4)	13.7 (0.4)	8.1 (0.4)	4.6 (0.4)
	$T - \hat{T}$	4.93	3.02	2.40	1.91
	g_Y	1.42	2.36	2.29	2.02
1.0	$E_Y + E_B$	34.0 (0.4)	15.5 (0.4)	10.3 (0.4)	6.6 (0.4)
	$T - \hat{T}$	4.93	3.12	2.55	2.09
	g_Y	1.42	2.27	2.19	1.94

The inclusion of CCS investment tends to reduce industrial CO_2 emissions from BAU. When the share of investment in CCS is increased (f = 0.3, second row), one notes that for $\tau_b = 0.075$, the 2100 deforestation emissions are 0.4 $GtCyr^{-1}$ (value in parentheses) while industrial CO_2 emissions slightly decrease. This contributes to a slight decline in SAT and consequently, to a small increment in per capita GDP. Further investment share in CCS, namely f = 0.6 and 1.0, causes CO_2 emissions to increase back slightly. This increase, in turn, contributes to a small increment in SAT and consequently, to a slight decline in per capita GDP.

From the table, we notice that 100 % investment in CCS, i.e. f = 1.0, is slightly less efficient than the combined investment in both low-carbon technologies and CCS technologies. A higher rate of GDP growth is observed when f = 0.3 and τ_b = 0.075. This corresponds to total emissions reduction from baseline of approximately 0.19 $GtCyr^{-1}$ at a total CCS cost of about USD149 $(tC)^{-1}$ by 2100. This cost is within the range of the cost of CCS as given in the literature, cf. Subsection 3.3.2 and references there. Note that more investment in CCS (f = 0.6 and 1), along with an increasing abatement share (τ_b = 0.11 and 0.145), also contributes to a decline in per capita GDP growth rate from what is found in the f = 0.3 row and τ_b = 0.075 column.

In the f = 1.0 row, we note that inclusion of CCS without abatement in the energy sector also has potential for global change mitigation, although a little less efficiently.

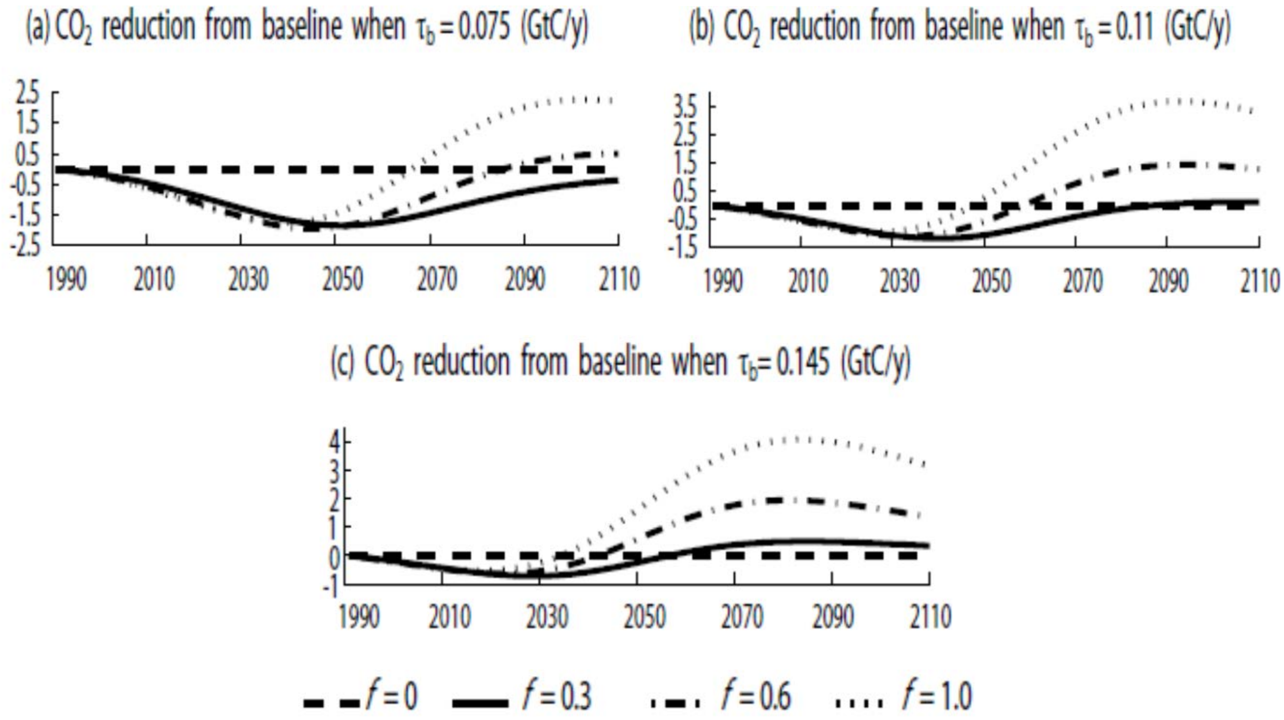

Fig. 4 Evolution in time of reduction in CO_2 emissions from baseline, for $B \neq 0$ and $R_d = 0$, and for f-values that range from 0 (0 % investment in CCS) to 1.0 (100 % investment in CCS). (a) τ_b = 0.075, (b) τ_b =0.11, and (c) τ_b = 0.145; see legend for curves, with *f* = 0 — dashed, *f* = 0.3 — solid, *f* = 0.6 — dash-dotted, and *f* = 1.0 — dotted

In Figure 4, the time-dependent evolution of the reduction in CO_2 emissions from baseline for the different values of f is shown, from 1990 to 2100, keeping the deforestation reduction equal to 0. Figure 4a shows that initial investment in CCS of 30 %, when the abatement share is $\tau_b = 0.075$, leads to CO_2 emissions that are below control by 2100. Further investment in CCS, of

60 % and 100 % respectively, leads to an initial reduction, followed by an increment in CO_2 emissions by 2100. We also note that, with an increased abatement share of $\tau_b = 0.11$ (Figure 4b) and 0.145 (Figure 4c), this effect is amplified, i.e., the emissions decrease at the beginning and then increase even more by 2100.

4.5 Integrations with inclusion of deforestation control

In Table 8, the CCS investment share is taken to be 0 and we analyze the effect of increasing deforestation control with different values of τ_b, in the absence of CCS investments, $f = 0$. We first consider the $\tau_\mathrm{b} = 0.075$ column and note that, generally, an increase of R_d contributes to an increase of biomass; such an increase, in turn, contributes to the sequestration of atmospheric CO_2 due to photosynthesis, as evidenced by the reduction in the $C/\hat{C}$ ratio.

For instance, we note that increasing R_d from 0 to 1.2 gives a per annum sequestration of atmospheric CO_2 of 0.26 GtCyr^{-1} between 1990 and 2100. Comparing with other studies on biomass photosynthetic sequestration of atmospheric CO_2 due to afforestation, this particular annual amount of CO_2 fertilization agrees quite well with the average range of 0.16–1.1 GtCyr^{-1} by 2100 in Canadell and Raupach (2008), and with the range of 0.1–0.4 GtCyr^{-1} obtained by Luo and Moonry (1996); see also Polglase et al. (2013).

Table 8 Variable values for year 2100, with deforestation emissions in parenthesis, for runs with inclusion of deforestation control scenario

τ_b R_d		0	0.075	0.11	0.145
0	$E_Y + E_B$	34.0 (0.4)	13.3 (0.4)	6.7(0.4)	3.0 (0.4)
	$C/\hat{C}$	2.90	1.94	1.64	1.44
	$T - \hat{T}$	4.93	3.12	2.37	1.78
	g_Y	1.42	2.30	2.32	2.08
0.1	$E_Y + E_B$	34.2 (0.3)	13.3 (0.3)	6.7 (0.3)	2.9 (0.3)
	$C/\hat{C}$	2.90	1.93	1.63	1.43
	$T - \hat{T}$	4.93	3.11	2.36	1.76
	g_Y	1.42	2.31	2.33	2.09
0.5	$E_Y + E_B$	34.7 (0.2)	13.4 (0.2)	6.6 (0.2)	2.8 (0.2)
	$C/\hat{C}$	2.88	1.92	1.62	1.42
	$T - \hat{T}$	4.91	3.08	2.31	1.71
	g_Y	1.45	2.34	2.35	2.10
1.0	$E_Y + E_B$	35.3 (0)	13.5(0)	6.6 (0)	2.7 (0)
	$C/\hat{C}$	2.87	1.90	1.60	1.40
	$T - \hat{T}$	4.88	3.03	2.25	1.64
	g_Y	1.48	2.37	2.38	2.12
1.2	$E_Y + E_B$	35.6 (-0.1)	13.6 (-0.1)	6.6 (-0.1)	2.6 (-0.1)
	$C/\hat{C}$	2.86	1.89	1.59	1.39
	$T - \hat{T}$	4.87	3.01	2.23	1.61
	g_Y	1.49	2.39	2.39	2.13

The reduction in atmospheric CO_2 due to biomass photosynthesis contributes to a decrease in SAT and consequent damages. These actually increase the GDP growth slightly. The improvements due to R_d are nevertheless small compared to the effect of low-carbon technologies or CCS. It has to be said, however, that besides reducing carbon emissions, reduced deforestation also delivers other benefits, such as biodiversity conservation and watershed and soil quality protection (Chomitz and Kumari 1998; Ebeling and Yasué 2008; Eriksson 2013; Sedjo et al. 1995;

Stickler et al. 2009; Strassburg et al. 2012; World Bank 2011). The latter benefits are not accounted for in the present version of our CoCEB model. In fact, little attention has been paid so far in the literature to the presence of these co-benefits of deforestation control when calculating its cost (Phan et al. 2014, Table 1).

4.6 A mix of mitigation measures

Even though it is beyond this thesis's ability to predict a realistic international emissions mitigation regime, CoCEB simulations suggest that best results are obtained by combining the various mitigation measures discussed. This was found in Table 7 and Figure 4, where we noted that 100 % investment in CCS or low-carbon technologies is slightly less efficient than the combined investment in both technologies.

Table 9 Target values of key variables for our policy scenarios at year 2100, with $f = 0.3$ and $R_d = 0.1$

τ_b	Emissions $E_Y + E_B$ ($\mathrm{GtC\,yr^{-1}}$)	CO_2 $C/\hat{C}$	Biomass B (GtC)	Deviation from pre-industrial $T - \hat{T}$ (^{0}C)	Damages (% GDP)	GDP growth g_Y ($\%\mathrm{yr^{-1}}$)
0	34.2	2.9	829	4.9	24.4	1.42
0.075	12.8	1.9	782	3.0	8.7	2.40
0.11	6.8	1.6	769	2.3	4.8	2.36
0.145	3.4	1.4	761	1.8	2.6	2.08

For illustration purposes, we chose now a 30 % investment in CCS technologies and a deforestation control of $R_d = 0.1$, while the other parameter values are as in Table 1. The values of CO_2 emissions and concentration, temperature, damage and GDP growth at year 2100 are shown in Table 9 for the four scenarios corresponding to the abatement share τ_b = 0, 0.075, 0.11 and 0.145.

From the table, the scenario corresponding to $\tau_b = 0$ attains total emissions of 34.2 GtCyr^{-1} by 2100. This leads to an atmospheric CO$_2$ concentration of 1727 GtC, i.e. about 2.9 times the pre-industrial level at that time. As a consequence, global average SAT will rise by 4.9 ^{0}C from the pre-industrial level with a corresponding damage to the per capita GDP of 24.4 % and a GDP growth of 1.42 %. This compares well with the IPCC results for their RCP8.5 scenario (IPCC 2013; Riahi et al. 2007; Rao and Riahi 2006).

For the scenarios corresponding to τ_b = 0.075, 0.11 and 0.145, the results obtained are slightly better than those in Table 7 when f = 0 or 1.0. We also note that, for τ_b = 0.075 and 0.11, the CO$_2$ emissions per year, as well as the CO$_2$ concentrations and SAT deviations from pre-industrial level in year 2100, agree fairly well with those of RCP6.0 and RCP4.5 respectively (Clerke et al. 2007; Fujino et al. 2006; Hijioka et al. 2008; IPCC 2013; Smith and Wigley 2006; Wise et al. 2009).

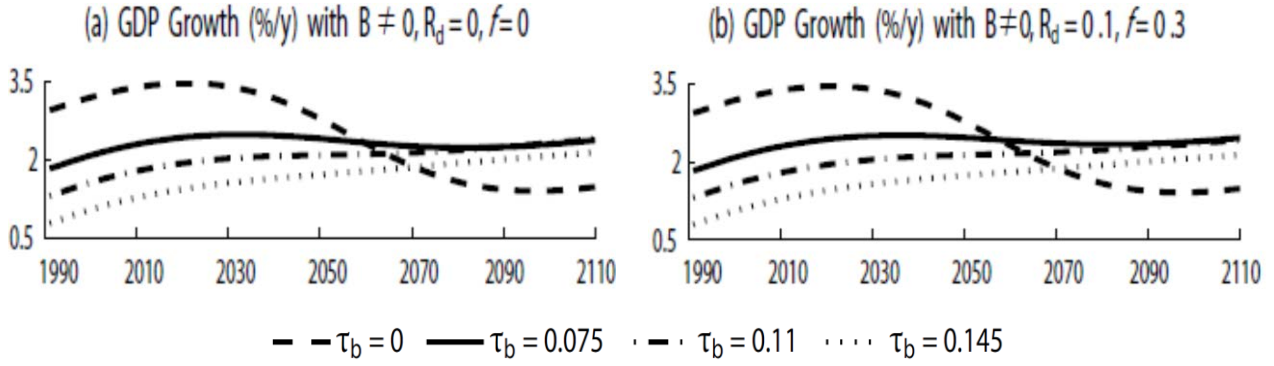

Fig. 5 GDP growth over time, with biomass module ($B \neq 0$), as a function of abatement share values τ_b between 0.0 (no abatement) and 0.145. (a) $R_d = 0$ and $f = 0$; and (b) $R_d = 0.1$ and $f = 0.3$; see legend for curve identification

Figure 5 plots the per capita GDP growth curves with time for the f = 0 and $R_d = 0$ scenario (Figure 5a) and for f = 0.3 and $R_d = 0.1$ scenario (Figure 5b). In both panels, we notice that per capita GDP growth on the paths with nonzero abatement share, $\tau_b \neq 0$, lies below growth on the BAU path, i.e., when using $\tau_b = 0$, for the earlier time period, approximately between 1990 and 2060 in Figure 5a and approximately between 1990 and 2058 in Figure 5b.

Later though, as the damages from climate change accumulate on the BAU path, GDP growth in the BAU scenario slows down and falls below the level on the other paths, i.e. the paths cross and mitigation strategies pay off in the longer run. We also observe that the growth in Figure 5b — with 30 % investment in CCS technologies and 70 % investment in low-carbon technologies, together with a deforestation control of 10 % — is slightly higher than that in Figure 5a.

CHAPTER 5

SENSITIVITY ANALYSIS

The estimates for the cost of CCS and of deforestation control are still very uncertain in the mitigation literature. For this reason, the thesis conducted an analysis to ascertain the robustness of the CoCEB model's results and to clarify the degree to which they depend on five key parameters: the damage function parameters m_1 and χ, the low-carbon abatement efficiency parameter α_τ, CCS abatement efficiency parameter α_ω, and the pi's parameters of Equation (27). The last two parameters effectively govern the cost of CCS and deforestation control. The values of these parameters are varied below in order to gain insight into the extent to which particular model assumptions affect results in Chapter 4 above.

5.1 Damage function parameters m_1 and χ

The thesis modifies the values of the parameters m_1 and χ by +50 % and –50 % from their respective values $m_1 = 0.0067$ and $\chi = 2.43$ in Tables 1–9 above. It examines how that affects model results for year 2100. In Table 10 are listed the per annum CO_2 emissions, CO_2 concentrations, SAT, damages, and growth rate of per capita GDP. All parameter values are as in Table 1, including $\alpha_\tau = 1.8$, $f = 0$, $B = 0$, and $R_d = 0$.

From the table, it is noticed that reducing m_1 by 50 % lowers the damages to per capita GDP from 26.9 to 20.3 %, i.e., a 24.5 % decrease on the BAU ($\tau_b = 0$) path. This depresses the economy less and contributes to higher CO_2 emissions of 50.8 GtCyr^{-1}. On the other hand, increasing m_1 by 50 % increases the damages from 26.9 to 30.3 %, i.e., a 12.6 % increase on the BAU path. This depresses the economy more and lowers CO_2 emissions in 2100 to 20.4 GtCyr^{-1}.

Table 10 Policy scenario values at year 2100 with $\alpha_\tau = 1.8$, $f = 0$, $B = 0$, $R_\mathrm{d} = 0$, varying m_1, and χ

		τ_b	Emissions E_Y (GtCyr^{-1})	CO$_2$, $C/\hat{C}$	Deviation from pre-industrial, $T-\hat{T}$ (^{0}C)	Damages (% GDP)	GDP growth g_Y (%yr^{-1})
m_1=0.0034 (-50 %)	χ=2.34	0	50.8	3.7	5.9	20.3	1.8
		0.075	16.0	2.2	3.7	7.3	2.5
		0.11	7.3	1.8	2.8	3.8	2.4
		0.145	2.8	1.5	2.1	1.9	2.1
m_1=0.01 (+50 %)		0	20.4	2.8	4.7	30.3	0.7
		0.0175	9.3	2.0	3.2	14.4	1.8
		0.11	5.0	1.7	2.5	8.6	2
		0.145	2.2	1.5	1.9	4.8	1.9
χ=1.215 (-50 %)	m_1=0.0067	0	99.6	4.5	6.7	6.3	3.6
		0.075	19.1	2.3	3.8	3.3	3.0
		0.11	7.8	1.8	2.8	2.3	2.6
		0.145	2.9	1.5	2.1	1.6	2.2
χ =3.645 (+50 %)		0	6.0	2.1	3.6	41.6	-0.2
		0.075	4.9	1.8	2.8	22.9	1.0
		0.11	3.5	1.6	2.4	13.5	1.6
		0.145	1.9	1.5	1.9	6.6	1.8

The sensitivity to the nonlinearity parameter χ is considerably higher. Decreasing it by 50 % reduces the damages to per capita GDP from 26.9 to about 6.3 %, i.e., a 76.6 % reduction on the BAU path. This contributes to higher economic growth and higher emissions of 99.6 GtCyr^{-1}. Conversely, increasing χ by 50 % increases the damages to per capita GDP from 26.9 to about 41.6 %, i.e., a 54.6 % increase on the BAU path. This contributes to a decrease in economic growth and to lower emissions of 6 GtCyr^{-1} in the year 2100.

In Figure 6 are plotted the GDP growth curves with time for the experiments summarized in Table 10. It is clear from the figure that the growth rate of per capita GDP is more sensitive to the nonlinearity parameter χ than to m_1.

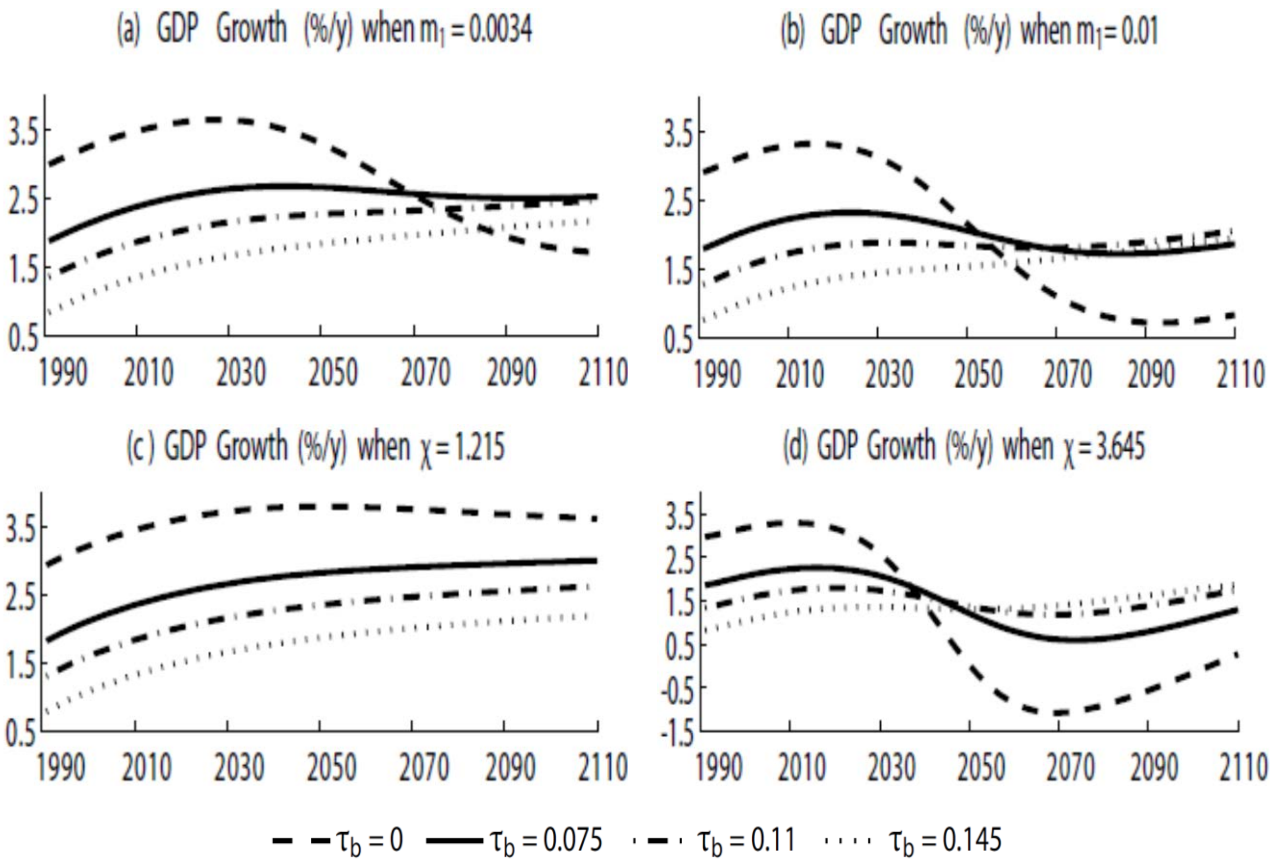

Fig. 6 GDP growth over time as a function of abatement share values τ_b between 0.0 and 0.145; see legend for curve color, while $\alpha_\tau = 1.8$, $f = 0$, $B = 0$, $R_d = 0$. Panels (a, b) m_1 is larger or smaller by 50 % than the value in Tables 1–9; (c, d) same for the nonlinearity parameter χ

A decrease of m_1 by 50 % pushes the crossover point further into the future, from year 2058 to 2070 (Figure 6a), while an increase by 50 % pulls the crossover point closer to the present, to about 2053 (Figure 6b). Decreasing χ by 50 %, on the other hand, pushes the crossover point even further away, past the end of the century (Figure 6c), while an increase of χ by 50 % pulls it from year 2058 to about 2040 (Figure 6d).

5.2 Robustness to changes in the low-carbon abatement efficiency parameter α_τ

Next, the thesis modifies the value of the parameter α_τ by +50 and –50 % from the standard value of $\alpha_\tau = 1.8$ used in Tables 1–10 above, and examine in Table 11 how that affects the model emissions reduction from baseline by the year 2100, as well as the per capita low-carbon abatement costs and the per capita damage costs.

Table 11 Effect of varying α_τ by year 2100; $f = 0$, $B = 0$, $R_d = 0$, other parameter values as in Table 1

	Abatement share τ_b	% reduction of emissions (E_Y) from baseline	Per capita abatement costs (% Y)	Per capita damage costs (% Y)	GDP growth g_Y (%yr^{-1})
Abatement efficiency = 0.9 (-50 %)	0	0	0	26.9	1.1
	0.075	48	1.5	13.6	1.8
	0.11	67	2.2	8.8	1.9
	0.145	81	2.9	5.5	1.8
Abatement efficiency = 2.7 (+50 %)	0	0	0	26.9	1.1
	0.075	71	1.5	9.4	2.3
	0.11	90	2.2	4.4	2.4
	0.145	98	2.9	1.9	2.1

A 50 % decrease of the low-carbon abatement efficiency gives $\alpha_\tau = 0.9$ in the upper half of the table. There is a substantial decrease in emissions reduction for all three scenarios with $\tau_b > 0$, compared to Table 4, and hence more damages for the same abatement costs. Furthermore, the increased damages increase the depression of the economy and contribute to low economic growth.

On the other hand, a 50 % increase in the abatement efficiency, to $\alpha_\tau = 2.7$, leads to an increase in the emissions reduction from baseline by 2100. This reduces the damages and hence lessens the depression to the economy, enabling economic growth to increase.

5.3 Robustness to changes in the CCS abatement efficiency parameter α_ω

The thesis modifies the value of the parameter α_ω by –84 and +84 % from the standard value of $\alpha_\omega = 46.1$ used in Tables 1–11 above and examine in Table 12 how that affects the model emissions reduction and the GDP growth from baseline by the year 2100. The idea is to check how the results are affected by the hypothesis that the costs of CCS were much higher or much lower than the ones used here, and compared to the cost uncertainties found in the literature. The low value of α_ω is equivalent to USD615 $(\mathrm{tC})^{-1}$ by 2100, while the high value is equivalent to USD548 $(\mathrm{tC})^{-1}$; these values agree quite well with those given in the literature. We recall once more that the costs everywhere in this thesis are expressed in constant 1990 USD.

Table 12 Effect of varying α_ω by year 2100; $B \neq 0$, $R_\mathrm{d} = 0$, $\tau_b = 0.075$, and all other parameter values as in Table 1

f	Reduction of emissions (E_Y) from baseline ($\mathrm{GtC\,yr^{-1}}$)	CCS abatement cost (USD $(\mathrm{tC})^{-1}$)	Per capita GDP growth g_Y ($\%\mathrm{yr}^{-1}$)
0	0.19– (0.19) –0.19	0– (0) –0	2.30– (2.30) –2.30
0.3	0.20– (0.19) –0.17	147– (149) –153	2.46– (2.39) –2.22
0.6	0.19– (0.19) –0.16	306– (311) –330	2.42– (2.36) –2.14
1.0	0.17– (0.17) –0.14	548– (558) –615	2.32– (2.27) –2.02

Each entry in the table — for total emissions reduced, CCS abatement cost, and the per capita GDP growth — appears as three numbers: the standard integrated values for $\alpha_\omega = 46.1$ (in parentheses) in the middle, the modified values for the standard +84 % on the left-hand side, and the modified values for the standard –84 % on the right-hand side. From the observed span of the expected values, we notice that in the case of cheap CCS, at USD548 $(tC)^{-1}$, the $f = 1.0$ case gives more or less the same emissions reduction and GDP growth as $f = 0$

Comparing the efficiency of CCS and low-carbon technologies, which depend on their cost estimation, we note that given the uncertainties, low-carbon can be either slightly more efficient or equally efficient. The qualitative result that a mix of the two is better than 100 % of the one or 100 % of the other is quite robust.

5.4 Robustness to changes in the deforestation control cost parameters

Taking $\tau_b = 0.075$, $f = 0.3$, and with the standard values (given in Table 1) of the R_{d} cost parameters π_1, π_2, π_3, π_4, and π_5, we note that by increasing R_{d} from 0 to 0.1, the deforestation emissions are reduced from approximately 0.4 to 0.3 GtCyr^{-1} at a total cost of USD164 $(tC)^{-1}$, while the per capita GDP growth would be of 2.40 $\%\mathrm{yr}^{-1}$ by 2100.

We now vary, simultaneously, the R_{d} cost parameters from the standard values so so as to span the range of costs given by Phan et al. (2014). A variation of –99 % gives a total cost of USD0.9 $(tC)^{-1}$ and that of +47 % gives a total cost of USD246 $(tC)^{-1}$. Even using these two extreme values, no significant effect is observed on the integration of the CoCEB model. The results in both cases only differ from Table 9 in the third decimal place.

CHAPTER 6

CONCLUSIONS AND WAY FORWARD

6.1 Summary

This thesis introduced a simple coupled climate─economy─biosphere (CoCEB) model with the goal of understanding the various feedbacks involved in the system and also for use by policy makers in addressing the climate change challenge. In this thesis, economic activities are represented through a Cobb-Douglas output function with constant returns to scale of the two factors of production: per capita physical capital and per capita human capital. The income after tax is used for investment, consumption, and abatement. Climate change enters the model through the emission of GHGs arising in proportion to economic activity. These emissions accumulate in the atmosphere and lead to a higher global mean surface air temperature (SAT). This higher temperature then causes damages by reducing output according to a damage function. A biomass equation, representing the biosphere module, was also added and the related exchanges of CO_2 taken into consideration. The CoCEB model, as formulated here, was summarized as Equations (32) in Section 3.6.

This thesis assumed the hypothesis that the current global warming is caused largely by anthropogenic increase in the CO_2 concentration in the Earth's atmosphere. It also assumed that all nations participate in carbon emissions mitigation activities. But as of 2013, there were no effective international agreements to limit the emissions of CO_2 and other GHGs (Nordhaus 2013b, p. 11)

Using this model, the thesis investigated in Chapter 4 the relationship between investing in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system through abatement activities, as well as the time evolution, from 1990 to 2100, of the growth rate of the economy under threat from climate change–related damages. This thesis has also investigated the relationship between the long-run effects of using CCS and deforestation control, and the long-term growth rate of the economy. The framework developed allows one to investigate policy sensitivity to the choice of key parameters. We analyzed in particular the effect of the parameters setting the costs of the different means of climate change mitigation: in the present work, the parameter values tested spanned the range of cost values found in the mitigation literature.

The CoCEB model shows that taking no abatement measures to reduce GHGs leads eventually to a slowdown in economic growth; see also Kovalevsky and Hasselmann (2014, Figure 2).

This slowdown implies that future generations will be less able to invest in emissions control or adapt to the detrimental impacts of climate change (Krakauer 2014). Therefore, the possibility of a long-term economic slowdown due to lack of abating climate change (Kovalevsky and Hasselmann 2014) heightens the urgency of reducing GHGs by investing in low-carbon technologies, such as electric cars, biofuels, CO_2 capturing and storing (CCS), renewable energy sources (Rozenberg et al. 2014), and technology for growing crops (Wise et al. 2009). Even if this incurs short-term economic costs, the transformation to a de-carbonized economy is both feasible and affordable according to Azur and Schneider (2002), Schneider (2008), Stern (2007), Weber et al. (2005), and would, in the long term, enhance the quality of life for all (Hasselmann 2010). The great flexibility and transparency of the CoCEB model has helped us demonstrate that an increase in the abatement share of investments yields a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions and, as a consequence, to a decrease in average global SATs and the ensuing damages. These results hold when considering the entire transition path from 1990 to 2100, as a whole.

The thesis has also shown that: (i) low investment in CCS contributed to a reduction in industrial carbon emissions and to an increase in GDP growth, but a further investment leads to a decrease in the reduction of emissions, as well as in the incremental GDP growth; (ii) enhanced deforestation control contributes to a reduction in both deforestation emissions and atmospheric CO_2 concentration, thus reducing the impacts of climate change; and (iii) the results in (i) remain very sensitive to the formulation of CCS costs. Conversely, the results for deforestation control were found to be less sensitive to the formulation of its cost. A large range of assumptions on these costs is found in the literature and the flexibility of the CoCEB model permitted us to span this range and to check the sensitivity of its results.

We found that per capita GDP growth on the paths with nonzero abatement share lies below growth on the Business as Usual (BAU) path for the earlier time period, approximately for 1990 to 2060, while GDP growth in the BAU scenario slows down and falls below the level on the other paths, i.e. the paths cross and mitigation strategies pay off in the longer run.

6.2 Discussion

The CoCEB model builds upon previous work on coupled models of global climate-economy interactions, starting from the pioneering work of Nordhaus (1994a), as extended in Greiner (2004) by the inclusion of endogenous growth. Greiner (2004) treated industrial CO_2 emissions as constant over time, while excluding the particular case of zero abatement activities (BAU); in fact, his model only applied for a minimum level of abatement. The thesis takes into account, more generally, emissions that depend on economic growth and vary over time, while including the case of abatement equal to zero, i.e. BAU. This was done by using logistic functions (Akaev 2012; Sahal 1981; see also, Probert et al., 2004, p. 108, and references therein) in formulating equations for the evolution of energy intensity and carbon intensity of energy throughout the whole 21st century (Akaev 2012).

In the climate modeling literature, the role of a full hierarchy of models, from the simplest to the most detailed ones, is well understood (e.g., Schneider and Dickinson 1974; Ghil 2001, and references therein). There is an even greater need for such a hierarchy to deal with the higher-complexity problems at the interface of the physico-chemical climate sciences and of socio-economic policy.

The CoCEB model lies toward the highly idealized end of such a hierarchy: it cannot, nor does it claim to, represent the details of the real world, but its simplicity is also a strength. Simple models do not allow one to provide a quantitative description of the fully coupled dynamics of the real climate–economy–biosphere system; on the other hand, though, the study of such models makes it possible to understand the qualitative mechanisms of the coupled-system processes and to evaluate their possible consequences.

More than just a simple model, CoCEB is a formal framework in which it is possible to represent in a simple way several components of the coupled system and their interactions. In this thesis, we showed as an example how to insert the effects of CCS and deforestation control. Several choices are possible in modeling these effects.

In this thesis, formulations taken from the literature have been integrated into the CoCEB framework. Doing so allowed us to treat low-carbon technologies, CCS and deforestation control consistently, and to translate the range of uncertainties on their relative cost into long-term effects on the climatic and economic system. The CoCEB framework also allowed us to evaluate the sensitivity of the results on the cost parameters.

Given the recent scientific evidence on global warming and its consequences, as documented in the numerous IPCC reports, the importance of climate change mitigation policies represents by now a consensus that is widely accepted by the climate community. Delaying action may mean that high temperatures and low growth are approached on a path that becomes irreversible. To prevent human society’s engaging on such a path, the IPCC reports (IPCC 1995, 2007a, 2014) propose a significant number of policy measures to prevent further emission of GHGs and a further rise of global temperature.

As measures leading toward a low-carbon economy, the IPCC Fourth Assessment Report emphasizes the role of technology policies to achieve lower CO_2 stabilization levels (IPCC 2007b, pp. 149–153, 218–219), a greater need for more efficient research and development efforts, and higher investment in new technologies over the next few decades, as emphasized further in IPCC (2012, Ch. 11, p. 878). The most recent assessment reports recommend government initiatives for funding or subsidizing alternative energy sources, including solar energy, ocean power, windmills, biomass, and nuclear fusion.

Forestry policies, particularly reduced deforestation, also emerge as additional low-cost measures for the reduction of carbon emissions. Reduced deforestation would cut carbon emissions and increased afforestation would sequester CO_2 from the atmosphere. As noted earlier, besides reducing carbon emissions, reduced deforestation can also deliver other benefits — such as biodiversity conservation and watershed and soil quality protection. It is advisable that future research focuses on the presence of the co-benefits of avoided deforestation, which could not be done in the present thesis nor in the existing mitigation literature. Overall, the IPCC stresses the fact that there are a number of effective policy measures available now that can reduce GHG emission.

This thesis considered technological abatement activities, as well as deforestation control to reduce the sources and enhance the sinks of GHGs, thereby lessening the radiative forcing that leads to temperature rise and economic impacts. Our results indicate that a pure CCS policy or a pure low-carbon technologies policy carry their own specific risks of being less efficient in combating climate change, a sentiment echoed by Akashi et al. (2014), Kalkuhl et al. (2014), Riahi et al. 2004a, Riahi et al. 2004b, Uyterlinde et al. (2006), among others.

Through our CoCEB framework, we have demonstrated that best results are obtained by combining the various mitigation measures discussed in this thesis, i.e., high investment in low-carbon technologies and low investment in CCS technologies, as well as inclusion of deforestation control. While we have also shown that certain results are robust to very substantial variations in parameter values, uncertainties do remain. Further research is, therefore, necessary, to reduce these uncertainties in the cost of the CCS technologies and of deforestation control.

Recent academic work has argued for a greater urgency to implement effective climate policies to combat climate change. Yet, to the best of our knowledge, no study has sufficiently explored the possibility of bringing together all the three mitigation measures under one coherent framework — including their impact on economic growth — as suggested here.

Another essential issue that has not been sufficiently addressed so far is how to reconcile and couple the IPCC's Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) being developed in the framework of more detailed integrated assessment models (IAMs) by the impacts, adaptation, and vulnerability communities; see Ebi et al. (2014); Kriegler et al. (2014); O'Neill et al. (2014); Rozenberg et al. (2014); Vuuren et al. (2014). We hope this thesis will serve as an illustrative pointer in this direction.

A finite–horizon optimal climate change control solution can be gotten by assuming that the government takes per capita consumption and the annual tax rate as given and sets abatement such that welfare is maximized. As to welfare, one can assume that it is given by the discounted stream of per capita utility times the number of individuals over a finite time horizon. The Pontryagin Maximum Principle (Hestenes 1966; Pontryagin et al. 1964; Sethi and Thompson 2000) is used to find the necessary optimality conditions for the *finite-horizon* control problem. The Maximum Principle for *infinite-horizon* control problems is presented in Michel (1982), Seierstadt and Sydsaeter (1987), Aseev and Kryazhimskiy (2004, 2007), and Maurer et al. (2013). For a modern theory of infinite–horizon control problems the reader is referred to Lykina et al. (2008). The determination of an optimal abatement path along the lines above will be the object of future work.

Concerning the damage function, Stern (2007) states that “Most existing IAMs also omit other potentially important factors – such as social and political instability and cross-sector impacts. And they have not yet incorporated the newest evidence on damaging warming effects,” and he continues “A new generation of models is needed in climate science, impact studies and economics with a stronger focus on lives and livelihoods, including the risks of large-scale migration and conflicts” (Stern 2013). Nordhaus (2013a) suggests, more specifically, that the damage function needs to be reexamined carefully and possibly reformulated in cases of higher warming or catastrophic damages. In the CoCEB model, an increase in climate-related damages has the effect of anticipating the crossover time, starting from which the abatement-related costs start paying off in terms of increased per capita GDP growth.

Another possible route toward a low-carbon future would include deployment of large-scale nuclear power as a substitute for fossil fuel power generation. The paper by Ahearne (2011) discusses the key questions about the future of nuclear energy: Will there be a nuclear renaissance? Is one already under way? Should there be a nuclear renaissance? What would it look like? If a renaissance is happening or could happen, what are the problems associated with that?

In his discussion of Ahearne's (2011) paper, Steinbruner (2011) argues that limitations on alternative options might force an extensive expansion of nuclear power generation, but that such an expansion cannot be undertaken safely on the basis of current reactor designs, current fuel cycle management practices, and current national security relationships. Instead, a strong case can be made for developing the more promising small, passively safe, and sealed reactor designs. On their part, Rabl and Rabl (2013), who compare the external costs of nuclear with those of the alternatives, argued that it would not be wise to retire nuclear plants precipitously, if the alternatives entail total (private + external) costs that are even higher. However, Rogner and Riahi (2013) analysis indicates that under a comprehensive and global mitigation effort, the stabilization of GHG concentrations at low levels (261.4 GtC) would be technically achievable even at high energy demand and with a nuclear phase-out. They identified that significant investments in energy efficiency improvements and energy demand reduction offer the most flexibility in energy supply options and may or may not include nuclear power; see also the discussions of Diesendorf (2014, pp. 142–143) on nuclear energy.

Now, the CoCEB model can be extended in several directions:

i) The next most interesting item on the research agenda is to let the biomass colonization rate and human population growth depend on the availability and quality of water, and to investigate how this will affect model feedbacks. Doing so will require a simple treatment of the water cycle.

ii) The CoCEB model can be regionalized, while maintaining its essential simplicity. For example, one might want to establish separate energy balance modules for the tropical and extratropical areas, and extend a similar separation to the economic module.

iii) Finally, even though there are several truly coupled IAMs (e.g., Ambrosi et al. 2003; Nordhaus and Boyer 1998; Stern 2007), these IAMs disregard variability and represent both climate and the economy as a succession of equilibrium states without endogenous dynamics. This can be overcome by introducing business cycles into the economic module (e.g., Akaev 2007; Hallegatte et al. 2008) and by taking them into account in considering the impact of both natural, climate–related and purely economic shocks (Groth et al. 2014; Hallegatte and Ghil 2008).

REFERENCES

1. Ahearne JF (2011) Prospects for nuclear energy. Energ Econ 33:572–580
2. Akaev AA (2007) Derivation of the general macroeconomic dynamics equation describing the joint interaction of long-term growth and business cycles. Dokl Math 76(3):879–881. doi:10.1134/S1064562407060191
3. Akaev AA (2012) Stabilization of the planetary climate in the twenty first century by transition to a new paradigm of energy consumption. Dokl Earth Sci 446(2):1180–1184
4. Akashi O, Hanaoka T, Masui T, Kainuma M (2014) Halving global GHG emissions by 2050 without depending on nuclear and CCS. Climatic Change 123:611–622. doi:10.1007/s10584-013-0942-x
5. Akhtar MK (2011) A system dynamics based integrated assessment modeling of global regional climate change: a model for analyzing the behavior of the social-energy economy-climate system, PhD thesis, The School of Graduate and Postdoctoral Studies, The University of Western Ontario London, Ontario, Canada
6. Alcamo J, Kreileman GJJ, Krol MS, Zuidema G (1994) Modeling the global society-biosphere-climate system: part 1: model description and testing. Water Air Soil Poll 76:1–35
7. Alcamo J, Leemans R, Kreileman E (eds) (1998) Global change scenarios of the 21st century: results from the IMAGE 2.1 model, Elsevier, Oxford, UK
8. Al-Fattah SM et al (2011) Carbon capture and storage: Technologies, policies, economics, and implementation strategies. CRC Press, New York, p 289
9. Al-Juaied M and Whitmore A (2009) Realistic costs of carbon capture. Discussion Paper 2009-08, Energy Technology Innovation Research Group, Belfer Center for Science and International Affairs, Harvard Kennedy School, Harvard University, USA
10. Ambrosi P et al (2003) Optimal control models and elicitation of attitudes towards climate

change. Environ Model Assess, 8(3):135–147. doi:10.1023/A: 1025586922143

11. Anderson RG et al (2011) Biophysical considerations in forestry for climate protection. Front Ecol Environ 9(3):174–182. doi:10.1890/090179
12. Aral, M. M. (2013) Climate change and human population dynamics. J Water Qual Expo Health, 6, 53–62, doi:10.1007/s12403-013-0091-5.
13. Arrhenius S (1896) On the influence of carbonic acid in the air upon the temperature of the ground. Philos Mag 41:237–276
14. Aseev SM and Kryazhimskiy AV (2004) The Pontryagin maximum principle and transversality condition for a class of optimal control problems with infinite time horizons. SIAM J Control Optim 43:1094–1119
15. Aseev SM and Kryazhimskiy AV (2007) The Pontryagin maximum principle and economic growth. P Steklov Inst Math 257(1):1–255
16. Azur C and Schneider SH (2002) Are the economic costs of stabilizing the atmosphere prohibitive? Ecol Econ 42:73–80. doi:10.1016/S0921-8009(02)00042-3
17. Barker T, Ekins P, Johnstone N (1995) Global warming and energy demand. London, UK: Routledge
18. Bauer N (2005) Carbon capturing and sequestration – an option to buy time. PhD thesis, Faculty of Economics and Social Sciences, University Potsdam
19. Beltran et al (2005) An ORACLE method to couple climate and economic dynamics. In: Haurie A and Laurent V (eds) The coupling of climate and economic dynamics: essays on integrated assessment. Amsterdam: Springer, p 70
20. Boero, G. (1995) Global warming – some economic aspects. Scot. J. Polit. Econ., 42, 99–112
21. Boero G, Clarke R, Winters LA (1991) The macroeconomic consequences of controlling greenhouse gases: a survey. DOE Environmental Economics Research Series, HMSO,

London

22. Bosetti V, Lubowski R, Golub A, Markandya A (2011) Linking reduced deforestation and global carbon market: implications for clean energy technology and policy flexibility. Environ Dev Econ 16:479–505
23. Bosetti V (2010) Technology-led climate policy – an alternative perspective. In: Lomborg B (ed) Smart solutions to climate change – comparing costs and benefits. Cambridge University Press
24. Canadell JG et al (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. P Natl Acad Sci USA 104(47):18866–18870
25. Canadell JG and Raupach MR (2008) Managing forests for climate change mitigation. Science 320:1456–1457
26. Carraro C (2002) Climate change policy: Models, controversies and strategies. In: Tietenberg T and Folmer H (eds) the international yearbook of environmental and resource economics 2002/2003: a survey of current issues. Edward Elgar, Cheltenham, UK
27. Chakravorty U, Roumasset J, Tse K (1997) Endogenous substitution among energy resources and global warming. J Polit Econ 105:1201–1234
28. Changnon SA, Kunkel KE, Reinke BC (1996) Impacts and responses to the 1995 heat wave: a call to action. B Am Meteorol Soc 77:1497–1506
29. Charney J et al (1979) Carbon dioxide and climate: a scientific assessment. National Academic Press, Washington, DC
30. Chen W-Y, Seiner J, Suzuki T, Lackner M (eds) (2012) Handbook of climate change mitigation. Springer New York, p 5. doi:10.1007/978-1-4419-7991-9
31. Chomitz KM and Kumari K (1998) The domestic benefits of tropical forests: a critical

review. World Bank Res Obser 13(1):13–35

32. Ciais P et al (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533
33. Clark CW (1990) Mathematical Bioeconomics. The optimal management of renewable resources. 2nd edn, Wiley, New York
34. Clarke L et al (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, D.C., USA, 154 pp
35. Clarke R, Boero G, Winters AL (1996) Controlling greenhouse gases – a survey of global macroeconomic studies. B Econ Res 48(4):0307–3378
36. Cline, W. R. (1992) Energy efficiency and greenhouse abatement costs (Comment on Lovins and Lovins), Climatic Change, 22, 95–97, doi:10.1007_bf00142960
37. Cobb CW and Douglas PH (1928) A theory of production. Am Econ Rev 18:139–165
38. Cox P and Stephenson D (2007) Climate change: a changing climate for prediction. Science 317:207–208. doi:10.1126/science.1145956
39. Creedy J and Guest R (2008) Sustainable preferences and damage abatement: value judgments and implications for consumption streams. Department of Economics, The University of Melbourne, Australia. Research Paper 1026
40. D’Andrea F, Provenzale A, Vautard R, De Noblet-Ducoudré N (2006) Hot and cool summers: multiple equilibria of the continental water cycle. Geophys Res Lett 33(24):Art. Nb. L24807
41. Davies EGR (2007) Modelling feedback in the Society-Biosphere-Climate system. PhD thesis, Department of Civil and Environmental Engineering, the University of Western

Ontario, London, Ontario, Canada

42. Davies EGR and SP Simonovic (2008) An integrated system dynamics model for analyzing behavior of the social-economic-climatic system: model description and model use guide. Water Resources Research Report no. 059, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London,Ontario, Canada, 233 pp. ISBN: (print) 978-0-7714-2679-7; (online) 978-0-7714-2680-3
43. Decanio SJ (2003) Economic models of climate change: a critique. Palgrave Macmillan Ltd
44. Dell M, Jones BF, Olken BA (2014) What do we learn from the weather? The new climate-economy literature. J Econ Lit 52(3):740–798. http://dx.doi.org/10.1257/jel.52.3.740
45. Diesendorf, M. (2014) Sustainable energy solutions for climate change mitigation, University of New South Wales Press Ltd, Sydney, Australia, 142–143
46. Dowlatabadi H (2000) Bumping against a gas ceiling. Climatic Change 46(3):391–407
47. Ebeling J and Yasué M (2008) Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits. Philos T Roy Soc B: 363:1917–1924
48. Ebi KL et al (2014) A new scenario framework for climate change research: background, process, and future directions. Climatic Change 122:363–372. doi:10.1007/s10584-013-0912-3
49. Edenhofer O, Carraro C, Hourcade JC (2012) On the economics of de-carbonization in an imperfect world. Climatic Change 114:1–8. doi:10.1007/s10584-012-0549-7
50. Edmonds JA et al (2004) Modelling greenhouse gas energy technology responses to climate change. Energy 29:1529–1536
51. Edwards N, Grepin H, Haurie A, Viguier L (2005) Linking climate and economic dynamics", In: Haurie A and Viguier L (eds) The Coupling of climate and economic dynamics: essays on

integrated assessment. Amsterdam: Springer

52. Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686–688
53. Eriksson M (2013) The role of the forest in an integrated assessment model of the climate and the economy. CERE Working Paper, 2013:1, Centre for Environmental and Resource Economics, Umeå School of Economics and Business, University of Umeå, Sweden
54. Erk N, Çabuk A, Ateş S (1998) Long-run growth and physical capital-human capital concentration. METU International Economic Conference II, 9–12 September 1998, Ankara
55. FAO (2010) Global forest resources assessment 2010: main report. Food and Agriculture Organization of the United Nations (FAO) Forestry Paper 163, Rome, Italy
56. Farmer GT and Cook J (2013) Climate change science: a modern synthesis, vol. 1: the physical climate. Dordrecht: Springer, p 4
57. Fiddaman, T.S. (1997) Feedback complexity in integrated climate-economy models, PhD thesis, MIT Sloan School of Management, Cambridge, MA
58. Fiddaman TS (2002) Exploring policy options with a behavioral climate-economy model. Syst Dynam Rev 18:243–267
59. Fischer C, Parry IWH, Pizer WA (2003) Instrument choice for environmental protection when technological innovation is endogenous. J Environ Econ and Manag 45:523–45
60. Fourier JB (1824) Remarques générales sur les températures du globe terrestre et des espaces planétaires. In: Annales de Chimie et de Physique, vol XXVII, pp 136–167
61. Fourier JB (1888) Mémoire sur les températures du globe terrestre et des espaces planétaires. In: Darboux GM (ed) Fourier JB Oeuvres vol 2. Gauthier-Villars et Fils:Paris, pp 97–125
62. Fujino J et al. (2006) Multi-gas mitigation analysis on stabilization scenarios using aim global model. Energy J, 0, 343–353

63. Galiana I and Green C (2010) Technology-led climate policy. In: Lomborg B (ed) Smart solutions to climate change – comparing costs and benefits. Cambridge University Press

64. Ghil M and Childress S (1987) Topics in geophysical fluid dynamics: atmospheric dynamics, dynamo theory and climate dynamics. Springer–Verlag, New York/Berlin/Tokyo, 485 pp

65. Ghil M (2001) Hilbert problems for the geosciences in the 21st century. Nonlinear Proc Geoph 8:211–222

66. Gollin D (2002) Getting income shares right. J Polit Econ 110, 458–474

67. Golosovsky M (2010) Hyperbolic growth of the human population of the Earth: analysis of existing models. In: Grinin L, Herrmann P, Korotayev A, Tausch A (eds) History and Mathematics: processes and models of global dynamics. Volgograd: Uchitel, pp 188–204

68. Greiner A (2004) Anthropogenic climate change in a descriptive growth model. Environ Dev Econ 9:645–662

69. Greiner A and Semmler W (2008) The global environment, natural resources and economic growth. Oxford University Press, NY, pp 60–68

70. Groth, A., Dumas, P., Ghil, M., and Hallegatte, S. (2014) Impacts of natural disasters on a dynamic economy, in: Extreme Events: Observations, Modeling and Economics, edited by: Chavez, M., Ghil, M., and Urrutia-Fucugauchi. J., AGU Monograph, Washington, DC, in press

71. Grübler A et al (1999) Dynamics of energy technologies and global change. Energ Policy 27:247–280

72. Gueymard C (2004) The Sun’s total and spectral irradiance for solar energy applications and solar radiation models. Sol Energy 76:423–452

73. Gullison RE et al (2007) Tropical forests and climate policy. Science 316:985–986

74. Hallegatte S and Ghil M (2008) Natural disasters impacting a macroeconomic model with

endogenous dynamics. Ecol Econ 68:582–592. doi:10.1016/j.ecolecon.2008.05.022

75. Hallegatte S, Ghil M, Dumas P, Hourcade JC (2008) Business cycles, bifurcations and chaos in a neoclassical model with investment dynamics. J Econ Behav Organ 67:57–77
76. Hannart A, Ghil M, Dufresne J-L, Naveau P (2013) Disconcerting learning on climate sensitivity and the uncertain future of uncertainty. Climatic Change 119:585–601. doi:10.1007/s10584-013-0770-z
77. Hans GK and Hans E (2013) Mathematics and climate. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, Pennsylvania
78. Hasselmann K (2010) The climate change game. Nat Geosci 3:511–512
79. Hestenes MR (1966) Calculus of variations and optimal control theory. New York: Wiley
80. Hijioka Y et al (2008) Global GHG emissions scenarios under GHG concentration stabilization targets. J Global Environ Eng 13:97–108
81. Holtz-Eakin D and Selden TM (1995) Stoking the fires? CO_2 emissions and economic growth. J Public Econ 57:85–101
82. Hourcade JC and P Shukla (2001) Global, regional and national costs and ancillary benefits of mitigation. In: Metz B, Davidson O, Swart R, Pan J (2001) Climate Change 2001: Mitigation. Cambridge University Press
83. IEA (2004) CO_2 capture and storage. International Energy Agency (IEA), Paris
84. IPCC (1995) Climate Change 1995: Impacts, adaptations and mitigation of climate change: scientific-technical analyses. Contribution of Working Group II to the Second Assessment Report of the IPCC, Watson RT, Zinyowera MC, Moss RH (eds). Cambridge University Press
85. IPCC (1996a) Climate Change 1995: The science of climate change. Contribution of Working Group I to the Second Assessment Report of the IPCC. Cambridge University Press

86. IPCC (1996b) Climate Change 1995: Economic and social dimensions of climate change. Contribution of Working Group III to the Second Assessment Report of the IPCC. Cambridge University Press, p 183

87. IPCC (2000) Land use, land-use change, and forestry. Cambridge: Cambridge University Press

88. IPCC (2001a) Climate Change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the IPCC, Houghton JT et al (eds). Cambridge University Press, 881 pp

89. IPCC (2001b) Climate Change 2001: Synthesis report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the IPCC, Watson RT (eds). Cambridge University Press

90. IPCC (2005) IPCC Special Report on carbon dioxide capture and storage. Prepared by Working Group III of the IPCC, Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds). Cambridge University Press, 442 pp

91. IPCC (2007a) Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Solomon S et al (eds). Cambridge University Press, 996 pp

92. IPCC (2007b) Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds). Cambridge University Press, 976 pp

93. IPCC (2007c) Climate Change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the IPCC, Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds). Cambridge University Press, 863 pp

94. IPCC (2007d) Climate Change 2007: Synthesis Report, Contribution of Working Groups I, II

and III to the Fourth Assessment Report of the IPCC, edited by: Pachauri RK and Reisinger A , IPCC, Geneva, Switzerland, 52 pp

95. IPCC (2012a) Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the IPCC, Field CB et al (eds). Cambridge University Press, 582 pp
96. IPCC (2012b) Renewable energy sources and climate change mitigation. A Special report of the IPCC, Edenhofer O et al (eds). Cambridge University Press, 1089 pp
97. IPCC (2013) Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC, Stocker TF et al (eds). Cambridge University Press, 1535 pp
98. IPCC (2014) Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the IPCC, available at: www.ipcc.ch/ (last access: 10-Oct-2014, 10:16 AM)
99. Johnson TL and Keith DW (2004) Fossil electricity and CO_2 sequestration: how natural gas prices, initial conditions and retrofits determine the cost of controlling CO_2 emissions. Energ Policy 32:367–382
100. Kalkuhl M, Edenhofer O, Lessmann K (2014) The role of carbon capture and sequestration policies for climate change mitigation. Environ Resource Econ, 60:55–80, doi:10.1007/s10640-013- 9757-5
101. Kaya Y (1990) Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris
102. Kellie-Smith O and Cox PM (2013) Emergent dynamics of the climate–economy system in the Anthropocene. Phil Trans R. Soc A 369:868–886. doi:10.1098/rsta.2010.0305

103. Kelly DL and Kolstad CD (1999) Integrated assessment models for climate change control. In: Tietenberg T and Folmer H (eds) The international yearbook of environmental and resource economics 2002/2003: a survey of current issues. Edward Elgar, Cheltenham, UK

104. Kemfert C (2002) An integrated assessment model of economy-energy-climate – the model Wiagem. Integrat Ass 3(4):281–298

105. Kindermann G et al (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. P Natl Acad Sci USA 105(30):10302–10307

106. Kirman AP (1992) Whom or what does the representative individual represent? J Econ Perspect 6(2):117–136

107. Kovalevsky DV and Hasselmann K (2014) Assessing the transition to a low-carbon economy using actor-based system-dynamic models, in: Proceedings of the 7th International Congress on Environmental Modeling and Software (iEMSs), edited by: Ames DP, Quinn NWT and Rizzoli AE, 15–19 June 2014, San Diego, California, USA, 1865–1872, available at: http://www.iemss.org/society/index.php/iemss-2014-proceedings (last access: 05-Oct-2014, 8:26 PM)

108. Krakauer NY (2014) Economic growth assumptions in climate and energy policy. Sustainability 6:1448–1461. doi:10.3390/su6031448

109. Kriegler E et al (2014) A new scenario framework for climate change research: the concept of shared climate policy assumptions. Climatic Change 122:401–414. doi:10.1007/s10584-013-0971-5

110. Labriet M and Loulou R (2003) Coupling climate damages and GHG abatement costs in a linear programming framework. Environ Model Assess 8:261–274

111. Leggett J, Pepper WJ, Swart RJ (1992) Emissions scenarios for IPCC: An update. In:

Houghton, JT, Callander BA, Varney SK (eds) Climate change 1992: The Supplementary Report to the IPCC Scientific Assessment; Cambridge University Press, Ch A3, pp 69–95

112. Lenton TM (2000) Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model. Tellus 52B:1159–1188

113. Levitus S, Antonov J, Boyer T (2005) Warming of the World ocean, 1955–2003. Geophys Res Lett 32:L02604. doi:10.1029/2004GL021592

114. Lotka, AJ (1925) Elements of Physical Biology. Baltimore MD: Williams and Wilkins

115. Luo Y and Mooney HA (1996) Stimulation of global photosynthetic carbon influx by an increase in atmospheric carbon dioxide concentration. In: Koch GW and Mooney HA (eds) Carbon dioxide and terrestrial ecosystems. San Diego. CA: Academic Press, Ch. 20, pp 381–397

116. Lykina V, Pickenhain S, Wagner M (2008) Different interpretations of the improper integral objective in an infinite horizon control problem. J Math Anal Appl 340:498–510

117. Mackey B, Prentice IC, Steffen W, House J (2013) Untangling the confusion around land carbon science and climate change mitigation policy. Nat Clim Change 3:552–557

118. Mankiw NG (2007) One answer to global warming: a new tax. The New York Times, 07/16/09

119. Manne AS, Mendelsohn R, Richels R (1995) MERGE – a model for evaluating regional and global effects of GHG reduction policies. Energ Policy 23(1):17–34

120. Manne AS, Richels RG, Edmonds JA (2005) Market exchange rates or purchasing power parity: does the choice make a difference to the climate debate? Climatic Change 71:1–8

121. Matsuoka Y, Kainuma M, Morita T (1995) Scenario analysis of global warming using the Asian-Pacific Integrated Model (AIM). Energ Policy 23(4–5):357–371

122. Maurer H, Preuß JJ, Semmler W (2013) Optimal control of growth and climate

change–exploration of scenarios. In: Cuaresma JC et al (eds) Green growth and sustainable development, dynamic modeling and econometrics in economics and finance 14. Springer-Verlag Berlin Heidelberg, pp 113–139. doi:10.1007/978-3-642-34354-4_6

123. McFarland JR, Reilly JM, Herzog HJ (2004) Representing energy technologies in top-down economic models using bottom-up information. Energ Econ 26:685–707

124. McGuffie K and Henderson-Sellers A (2005) A climate modelling primer. 3rd edn, Chichester: John Wiley, pp 81–85

125. McGuffie K and Henderson-Sellers A (2014) A climate modeling primer, 4th Edn., John Wiley Sons Inc, United States, 456 pp

126. Meadows DH, Randers J, Meadows D (2004) Limits to growth: the thirty year update. Chelsea Green Publishing Company, White River Junction, Vermont, United States

127. Meinshausen M, Raper SCB, Wigley TML (2008) Emulating IPCC AR4 atmosphere-ocean and carbon cycle models for projecting global-mean, hemispheric and land/ocean temperatures: MAGICC 6.0. Atmos Chem Phys Discuss 8:6153–6272

128. Mendelsohn R and Rosenberg NJ (1994) Framework for integrated assessments of global warming impacts. In: Frederick KD and Rosenberg NJ (eds) Assessing the impacts of climate change on natural resource systems. Reprinted from Climatic Change 28(1-2), 1994, Springer Science+Business Media, B.V, pp 15–44

129. Metz B (2010) Controlling climate change. Cambridge University Press, New York

130. Metz B and DP van Vuuren (2006) How, and at what costs, can low-level stabilization be achieved? – an overview, in: Avoiding dangerous climate change, edited by: Schellnhuber HJ, Cramer W, Nakićenović N, Wigley T, Yohe G, Cambridge University Press

131. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) (2007) Climate change 2007: mitigation of climate change. Contribution of Working Group III to the Fourth Assessment

Report of the IPCC. Cambridge University Press

132. Meyers RA (ed) (2012) Encyclopedia of sustainability science and technology. Springer New York, 12678 pp. doi:10.1007/978-1-4419-0851-3

133. Michel P (1982) On the transversality conditions in infinite horizon optimal control problems. Econometrica 50:975–985

134. Middleton R and Brandt A (2013) Using infrastructure optimization to reduce greenhouse gas emissions from oil sands extraction and processing. Environ Sci Technol 47:1735–1744

135. Min SK, Zhang X, Zwiers FW, Hegerl GC (2011) Human contribution to more intense precipitation extremes. Nature 470:378–381

136. Mitchell A (2009) Sea sick: the global ocean in crisis. McClelland and Stewart, Toronto

137. Mokhov II, Smirnov DA, Karpenko AA (2012) Assessments of the relationship of changes of the global surface air temperature with different natural and anthropogenic factors based on observations. Dokl Earth Sci 443(1):381–387

138. Morita T, Nakićenović N, Robinson J (2000) Overview of mitigation scenarios for global climate stabilization based on new IPCC emissions scenarios (SRES). Environ Econ Policy Stud 3(2):65–88

139. Morita T et al (2001) Greenhouse gas emission mitigation scenarios and implications, in: Climate change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the IPCC, edited by: Metz B, Davidson O, Swart R, and Pan J, Cambridge University Press. 700 pp

140. Nakićenović N and Swart RJ (eds) (2000) IPCC Special Report on Emissions Scenarios. Cambrigde University Press

141. Nordhaus WD (1992) An optimal transition path for controlling greenhouse gases. Science 258:1315–1319

142. Nordhaus WD (1993) Rolling the DICE– an optimal transition path for controlling greenhouse gases. Resour Energy Econ 15:27–50

143. Nordhaus WD (1994a) Managing the global commons: the economics of climate change. MIT Press, Cambridge

144. Nordhaus WD (1994b) Expert opinion on climatic change. Am Sci 82:45–51

145. Nordhaus WD (2007) The challenge of global warming: economic models and environmental policy. Yale University, New Haven, CT, USA

146. Nordhaus WD (2008) A question of balance. Princeton: Princeton University Press

147. Nordhaus WD (2010) RICE-2010 model. Yale University, New Haven, CT, USA

148. Nordhaus WD (2013a) Integrated Economic and Climate Modeling, in: Handbook of Computable General Equilibrium Modeling, edited by: Dixon, P. B., Jorgenson, D. W., Elsevier B.V., Oxford, UK, 1069–1131

149. Nordhaus WD (2013b) The climate casino: risk, uncertainty, and economics for a warming world. Yale University Press, New Haven and London, p 11

150. Nordhaus WD and Boyer J (1998) Roll the DICE again: the economics of global warming. Yale University

151. Nordhaus WD and Boyer J (2000) Warming the world: economic models of global warming. Cambridge, MA: MIT Press

152. O'Neill BC et al (2014) A new scenario framework for climate change research: the concept of shared socio economic pathways. Climatic Change 122:387–400. doi:10.1007/s10584-013-0905-2

153. Ortiz RA and Markandya A (2009) Integrated impact assessment models of climate change: a literature review. BC3 Working Paper Series, 2009-06, available online at http://www.bc3research.org/working_papers/view.html2009

154. Ortiz RA, Golub A, Lugovoy O, Markand A (2011) DICER- A tool for analyzing climate policies. Energ Econ 33:S41–S49

155. Pacala S and Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305:968–972

156. Parson EA (1994) Searching for integrated assessment: a preliminary investigation of methods and projects in the integrated assessment of global climatic change. Paper presented to the third meeting of the Harvard-CIESIN Commission on Global Environmental Change Information Policy, NASA Headquarters, Washington, DC

157. Phan T-HD, Brouwer R, Davidson M (2014) The economic costs of avoided deforestation in the developing world: a meta-analysis. J Forest Econ 20:1–16

158. Pizer WA (1999) Optimal choice of policy instrument and stringency under uncertainty. Resour Energy Econ, 21:255–287

159. Pizer WA (2002) Combining price and quantity controls to mitigate global climate change. J Public Econ, 85:409–434

160. Pizer WA (2006) Choosing price or quantity controls for greenhouse gases, in: The RFF Reader in Environmental and Resource Policy, 2nd Edn., edited by: Oates WE, Resources for the Future Press, Washington, DC, USA, 225–234

161. Polglase PJ et al (2013) Potential for forest carbon plantings to offset greenhouse emissions in Australia: economics and constraints to implementation. Climatic Change 121:161–175

162. Pontryagin LS, Boltyanski VG, Gramkrelidze RV, Miscenko EF (1964) The mathematical theory of optimal processes. Moscow: Fitzmatgiz. English translation: New York: Pergamon

163. Prinn R et al (1999) Integrated global system model for climate policy assessment:

feedbacks and sensitivity studies. Climatic Change 41(3–4):469–546

164. Prins G et al (2009) How to get climate policy back on course. Institute for Science, Innovation and Society. University of Oxford

165. Probert D et al (Eds.) (2004) Bringing technology and innovation into the boardroom: strategy, innovation and competences for business value. European Institute for Technology and Innovation Management, Basingstoke, Palgrave MacMillan

166. Rabl A (1996) Discounting of long-term costs: what would future generations prefer us to do? Ecol Econ 17:137–145

167. Rabl A and Rabl VA (2013) External costs of nuclear – greater or less than the alternatives. Energ Policy 57:575–584

168. Rao S and Riahi K (2006) The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. Multi-gas mitigation and climate policy. Energ J 3 (Special Issue):177–200

169. Rasch PJ (ed) (2012) Climate change modeling methodology: selected entries from the encyclopedia of sustainability science and technology. Springer Science+Business Media New York. doi:10.1007/978-1-4614-5767-1_8

170. Riahi K, Rubin ES, Taylor MR, Schrattenholzer L, Hounshell D (2004a) Technological learning for carbon capture and sequestration technologies. Energ Econ 26:539–564

171. Riahi K, Rubin ES, Taylor MR, Schrattenholzer L (2004b) Prospects for carbon capture and sequestration technologies assuming their technological learning. Energy 29:1309–1318

172. Riahi K, Gruebler A, Nakićenović N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc 74(7):887–935

173. Rogner M and Riahi K (2013) Future nuclear perspectives based on MESSAGE integrated assessment modeling. Energ Strat Rev 1(4):223–232

174. Rosenberg NJ (1991) Global warming initiatives: comments. In: Dornbusch R and Poterba JM (eds) Global warming: economic policy responses. Cambridge. MA: MIT Press, pp 330–334

175. Rose SK, Ahammad H, Eickhout B, Fisher B, Kurosawa A et al (2012) Land-based mitigation in climate stabilization. Energy Econ 34:365–380

176. Rotmans J (1990) IMAGE an Integrated Model to Assess the Greenhouse Effect, PhD thesis, Rijksuniversiteit Limburg, 295 pp

177. Rotmans J and de Vries B (1997) Perspectives on global change: the TARGETS approach. Cambridge: Cambridge University Press

178. Rotmans J et al (1997) The TARGETS model. In: Rotmans J and de Vries B (eds) Perspectives on global change: the TARGETS approach. Cambridge University Press, pp 33–54

179. Rotmans J and van Asselt MBA (2001) Uncertainty management in integrated assessment modeling: towards a pluralistic approach. Environ Monit Assess 69:101–130

180. Roughgarden T and Schneider SH (1999) Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. Energ Policy 27:415–429

181. Rozenberg J, Guivarch C, Lempert R, Hallegatte S (2014) Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. Climatic Change 122:509–522. doi:10.1007/s10584-013-0904-3

182. Sahal D (1981) Patterns of technological innovations. Addison-Wesley, London

183. Schlamadinger B and Bird DN (2007) Carbon accounting beyond 2012. Environ Sci Policy 10:269–394

184. Schneider SH and Dickinson RE (1974) Climate modeling. Rev Geophys Space Ge

12:447–493

185. Schneider SH (2008) Geoengineering: Could We or Should We Make It Work? Philos T Roy Soc A 366:3843–3862

186. Schrattenholzer L, Miketa A, Riahi K, Roehrl RA (2005) Achieving a sustainable global energy system identifying possibilities using long-term energy scenarios. ESRI Studies Series on the Environment, Edward Elgar Cheltenham, UK · Northampton, MA, USA

187. Schwartz SE (2007) Heat capacity, time constant, and sensitivity of Earth's climate system. J Geophys Res 112:D24S05. doi:10.1029/ 2007JD008746

188. Schwartz SE (2008) Reply to comments by G Foster et al, R Knutti et al and N Scafetta on ''Heat capacity, time constant, and sensitivity of Earth's climate system''. J Geophys Res 113:D15105. doi:10.1029/2008JD009872

189. Sedjo RA, Wisniewski J, Sample AV, Kinsman JD (1995) The economics of managing carbon via forestry: assessment of existing studies. Environ Resour Econ 6(2):139–165

190. Seierstadt A and Sydsaeter K (1987) Optimal Control Theory with Economic Applications. Elsevier B.V., Amsterdam: North-Holland, The Netherlands

191. Sethi, SP and Thompson GL (2000) Optimal control theory: applications to management science and economics (2nd edn). Norwell: Kluwer Academic

192. Smith SJ and Wigley TML (2006) Multi-gas forcing stabilization with the MiniCAM. Energ J SI3:373–391

193. Smulders S (1995) Entropy, environment, and endogenous growth. Int Tax Public Finan 2:319–340

194. Soden B and Held I (2006) An assessment of climate feedbacks in coupled ocean atmosphere models. J Clim 19:3354–3360. doi:10.1175/JCLI3799.1

195. Solow RM (1956) A contribution to the theory of economic growth. Q J Econ 70(1):65–

196. Stanton EA, Ackerman F, Kartha S (2008) Inside integrated assessment models: four issues in climate economics. Stockholm Environment Institute Working Paper, WP-US-0801

197. Steckel JC et al (2013) Development without energy? Assessing future scenarios of energy consumption in developing countries. Ecol Econ 90:53–67

198. Steinbruner J (2011) Comment. Energ Econ 33:581–583

199. Stephenson MH (2013) Returning Carbon to Nature: Coal, Carbon Capture, and Storage. Elsevier Inc., Waltham: MA 02451, USA, doi:http://dx.doi.org/10.1016/B978-0-12-407671-6.00001-X

200. Stern N (2007) The economics of climate change. The Stern review. Cambridge University Press

201. Stern N (2008) The economics of climate change. Am Econ Rev 98(2):1–37

202. Stern N (2013) The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. J Econ Lit 51(3):838–859. http://dx.doi.org/10.1257/jel.51.3.838

203. Stickler C et al (2009) The potential ecological costs and co-benefits of REDD: a critical review and case study from the Amazon region. Global Change Biol 15:2803–2824

204. Stott P et al (2000) External control of 20th century temperature by natural and anthropogenic forcings. Science 290:2133–2137. doi:10.1126/science.290.5499.2133

205. Strassburg BBN et al (2012) Impacts of incentives to reduce emissions from deforestation on global species extinctions. Nature Clim Change 2:350–355

206. Swan TW (1956) Economic growth and capital accumulation. Econ Rec 32 (63):334–361

207. Tavoni M, Sohngen B, Bosetti V (2007) Forestry and the carbon market response to stabilize climate. Energ policy 35(11):5346–5353

208. Tol SJR and Fankhauser S (1998) On the representation of impact in integrated assessment models of climate change. Environ Model Assess 3:63–74

209. Tol SJR (2010) Carbon dioxide mitigation. In: Lomborg B (ed) Smart solutions to climate change – comparing costs and benefits. Cambridge University Press

210. Toth FL (1995) Practise and progress in integrated assessments of climate change: a workshop overview. Energ Policy 239(4/5):253–267

211. United Nations (UN) (1992) United Nations Framework Convention on Climate Change. United Nations, Bonn, Germany

212. Uyterlinde MA et al (2006) The Contribution of CO_2 Capture and Storage to a Sustainable Energy System. Volume 4 in the CASCADE MINTS project, ECN-C--06-009, Energy Research Centre of the Netherlands (ECN), Netherlands

213. Uzawa H (1991) Global warming initiatives: the Pacific Rim. In Dornbusch R and Poterba JM (eds) Global warming: economic policy responses. Cambridge, MA: MIT Press, pp 275–324

214. Uzawa H (2003) Economic theory and global warming. Cambridge University Press

215. Vachris MA and Thomas J (1999) International price comparisons based on purchasing power parity. Mon Labor Rev (122):3–12

216. van Vuuren DP, Eickhout B, Lucas PL, den Elzen MGJ (2006a) Long-term multi-gas scenarios to stabilize radiative forcing - exploring costs and benefits within an integrated assessment framework. Energ J 27(Special Issue 3):201–233

217. van Vuuren DP et al (2006b) Stabilizing greenhouse gas concentrations at low levels: an assessment of options and costs. Report 500114002/2006, Netherlands Environmental Assessment Agency (MNP), Bilthoven, Netherlands

218. van Vuuren DP et al (2012) A proposal for a new scenario framework to support research

and assessment in different climate research communities. Global Environ Change 22:21–35, doi:10.1016/j.gloenvcha.2011.08.002

219. van Vuuren DP et al (2014) A new scenario framework for climate change research: scenario matrix architecture. Climatic Change 122:373–386. doi:10.1007/s10584-013-0906-1

220. van Wassenhove RS (2000) Using an optimal control model to simulate carbon dioxide-biomass interactions. PhD thesis, Rice University, Houston, Texas, USA

221. Volterra V (1931) Leçons sur la Théorie Mathématique de la Lutte pour la Vie. Paris: Gauthier- Villars

222. Weber M, Barth V, Hasselmann K (2005) A multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth. Ecol Econ 54 (2–3):306–327

223. Weitzman ML (1974) Prices vs. quantities. Rev Econ Stud 41(4):477–491

224. Weyant JP (1994) Integrated assessment of climate change: an overview and comparison of modeling approaches. Paper for the writing team 6/7 of working III Intergovernmental Panel on Climate Change Lead Authors Meeting, Geneva

225. Weyant J et al (1996) Integrated assessment of climate change: an overview and comparison of approaches and results. In: Bruce JP, Lee H, Haites EF (eds) Climate change 1995–economic and social dimensions of climate change. Contribution of working group III to the second assessment report of the IPCC. Cambridge University Press

226. Wigley TML (1991) A simple inverse carbon cycle model. Global Biogeochem Cy 5:373–382

227. Wise MA and Dooley JJ (2004) Baseload and peaking economics and the resulting adoption of a carbon dioxide capture and storage system for electric power plants. In: Rubin ES, Keith DW, Gilboy CF (eds). Proceedings of 7th International Conference on

Greenhouse Gas Control Technologies. Volume 1: Peer- Reviewed Papers and Plenary Presentations, IEA Greenhouse Gas Programme, Cheltenham, UK

228. Wise MA et al (2009) Implications of limiting CO_2 concentrations for land use and energy. Science 324:1183–1186

229. World Bank (2011) Estimating the opportunity costs of REDD+: A training manual, Version 1.3, World Bank Institute, Washington, DC, USA

APPENDICES

Appendix 1: Table of conversions

Notes: on units of weight used in this thesis.

Dealing with global/regional change involves large quantities. Here I use a Gigatonne (Gt) as the base unit of weight. This is related to other quoted weights as follows:

1. Gigatonnes of carbon (1 GtC = 3.667 $GtCO_2$)
2. 1 tonne = 10^6 g; 1Mg = 1tC ; 1TgC (teragrams of carbon) = 1MtC (Megatonnes of carbon);
3. 1 Pg (petagram) = 10^{15} g = 10^{12} kg = 1 Gt (gigatonne) = 1 billion metric tons of carbon;
4. 1Tg (teragram) = 10^{12} g = 10^9 kg = 0.001 Pg;
5. 1 ppmv = 2.13 GtC;
6. 1 ppmv = 1.9 M 10^{11} kg = 0.19 M Pg (where M is the molecular weight);
7. 1 ppm carbon dioxide = 2.12 Gt carbon;
8. 1 ppbv = 1.9 M 10^8 kg = 0.00019 M Pg.
9. Mg ha^{-1} = t ha^{-1} or 1 Mg ha^{-1} = 100 g m^{-2}
10. 1g dry matter (DM) $\approx$ 0.5 g C for woody tissues and slightly less for herbaceous plants.
    (The factor 1.9 comes from a combination of changing ppv to mass per volume and then integrating over the atmospheric column on Earth.)

Units for measuring energy

Rate of energy exchange is called *power.* A Watt (W) is a *power* Joule per second.

Appendix 2: Abstracts of selected publications

1. **Ogutu KBZ, D'Andrea F, Ghil M, Nyandwi C, Manene MM, Muthama JN (2015) Coupled Climate─Economy─Biosphere (CoCEB) model ─ Part 1: Abatement share and investment in low-carbon technologies. Earth Syst. Dynam. Discuss., 6, 819-863, doi:10.5194/esdd-6-819-2015.**

Abstract The Coupled Climate─Economy─Biosphere (CoCEB) model described herein takes an integrated assessment approach to simulating global change. By using an endogenous economic growth module with physical and human capital accumulation, this paper considers the sustainability of economic growth, as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change. Different types of fossil fuels and different technologies produce different volumes of carbon dioxide in combustion. The shares of different fuels and their future evolution are not known. We assume that the dynamics of hydrocarbon based energy share and their replacement with renewable energy sources in the global energy balance can be modeled into the 21st century by use of logistic functions. Various climate change mitigation policy measures are considered. While many integrated assessment models treat abatement costs merely as an unproductive loss of income, we consider abatement activities also as an investment in overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system. The paper shows that these efforts help to reduce the volume of industrial carbon dioxide emissions, lower temperature deviations, and lead to positive effects in economic growth.

2. **Ogutu KBZ, D'Andrea F, Ghil M, Nyandwi C, Manene MM, Muthama JN (2015) Coupled Climate─Economy─Biosphere (CoCEB) model ─ Part 2: Deforestation control and investment in carbon capture and storage technologies. Earth Syst. Dynam. Discuss., 6, 865–906, 2015, doi:10.5194/esdd-6-865-2015.**

Abstract This study uses the global climate─economy─biosphere (CoCEB) model developed in Part 1 to investigate economic aspects of deforestation control and carbon sequestration in forests, as well as the efficiency of carbon capture and storage (CCS) technologies as policy measures for climate change mitigation. We assume – as in Part 1 – that replacement of one technology with another occurs in terms of a logistic law, so that the same law also governs the dynamics of reduction in carbon dioxide emission using CCS technologies. In order to take into account the effect of deforestation control, a slightly more complex description of the carbon cycle than in Part 1 is needed. Consequently, we add a biomass equation into the CoCEB model and analyze the ensuing feedbacks and their effects on per capita gross domestic product (GDP) growth. Integrating biomass into the CoCEB and applying deforestation control as well as CCS technologies has the following results: (i) low investment in CCS contributes to reducing industrial carbon emissions and to increasing GDP, but further investment leads to a smaller reduction in emissions, as well as in the incremental GDP growth; and (ii) enhanced deforestation control contributes to a reduction in both deforestation emissions and in atmospheric carbon dioxide concentration, thus reducing the impacts of climate change and contributing to a slight appreciation of GDP growth. This effect is however very small compared to that of low-carbon technologies or CCS. We also find that the result in (i) is very sensitive to the formulation of CCS costs, while to the contrary, the results for deforestation control are less sensitive.