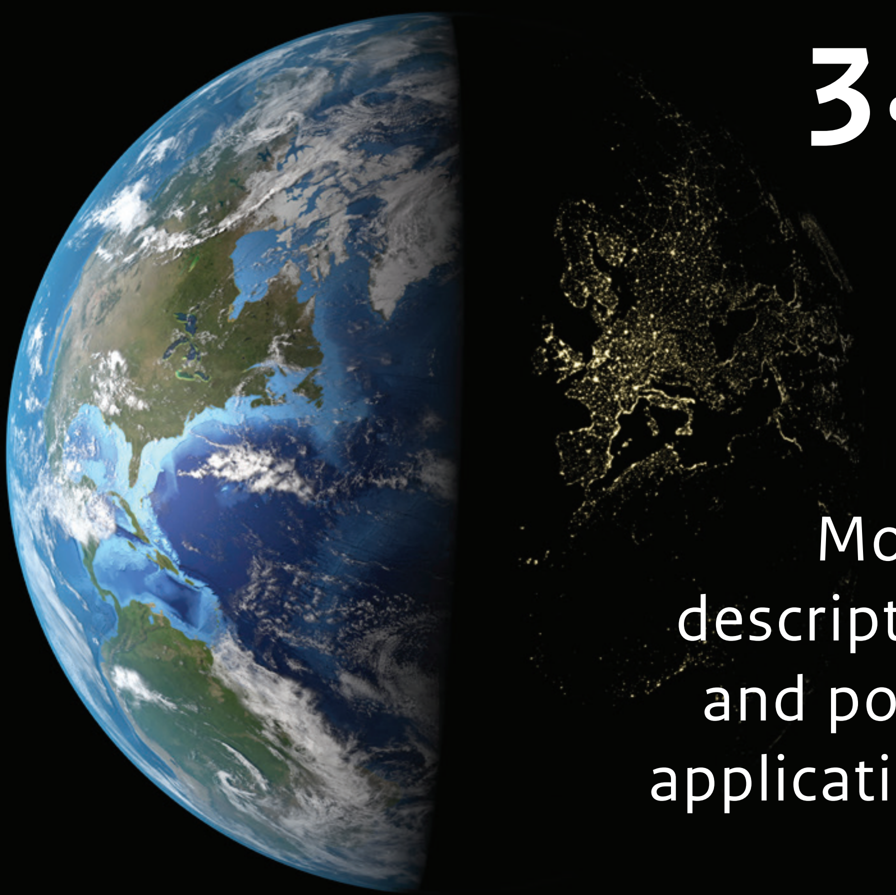
PBL Netherlands Environmental Assessment Agency

Integrated Assessment of Global Environmental Change with IMAGE 3.0



Model description and policy applications

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Editors
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The Hague, 2014

ISBN: 978-94-91506-71-0
PBL publication number: 735

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Acknowledgements
We are grateful for the cooperation with Potsdam Institute for Climate Impact Research, Wageningen UR and Utrecht University

Programming and website
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English editing
Annemieke Righart, Helen West

Graphics
Beeldredactie PBL

Cover photo
Colourbox.com

Design & layout
Textcetera, The Hague

Production co-ordination
PBL Publishers

Printer
Gildeprint, Enschede

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the field of environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all our studies. We conduct solicited and unsolicited research that is both independent and always scientifically sound.

Purpose and set-up of this book

- This book presents a complete and concise description of IMAGE 3.0, the Integrated Model to Assess the Global Environment version 3.0.

- The book has been prepared for those working at the science-policy interface, a client, partner or user for assessments with IMAGE 3.0.

- All model components are described in broad terms, focusing on functionalities, feedbacks, uncertainties, and policy applications. For more detail, reference is made to underlying scientific papers, listed at the end of each section as key publications.

- Chapter 1 (Introduction) and Chapter 2 (Overview IMAGE 3.0) provide an introduction to IMAGE 3.0, and the main model setup.

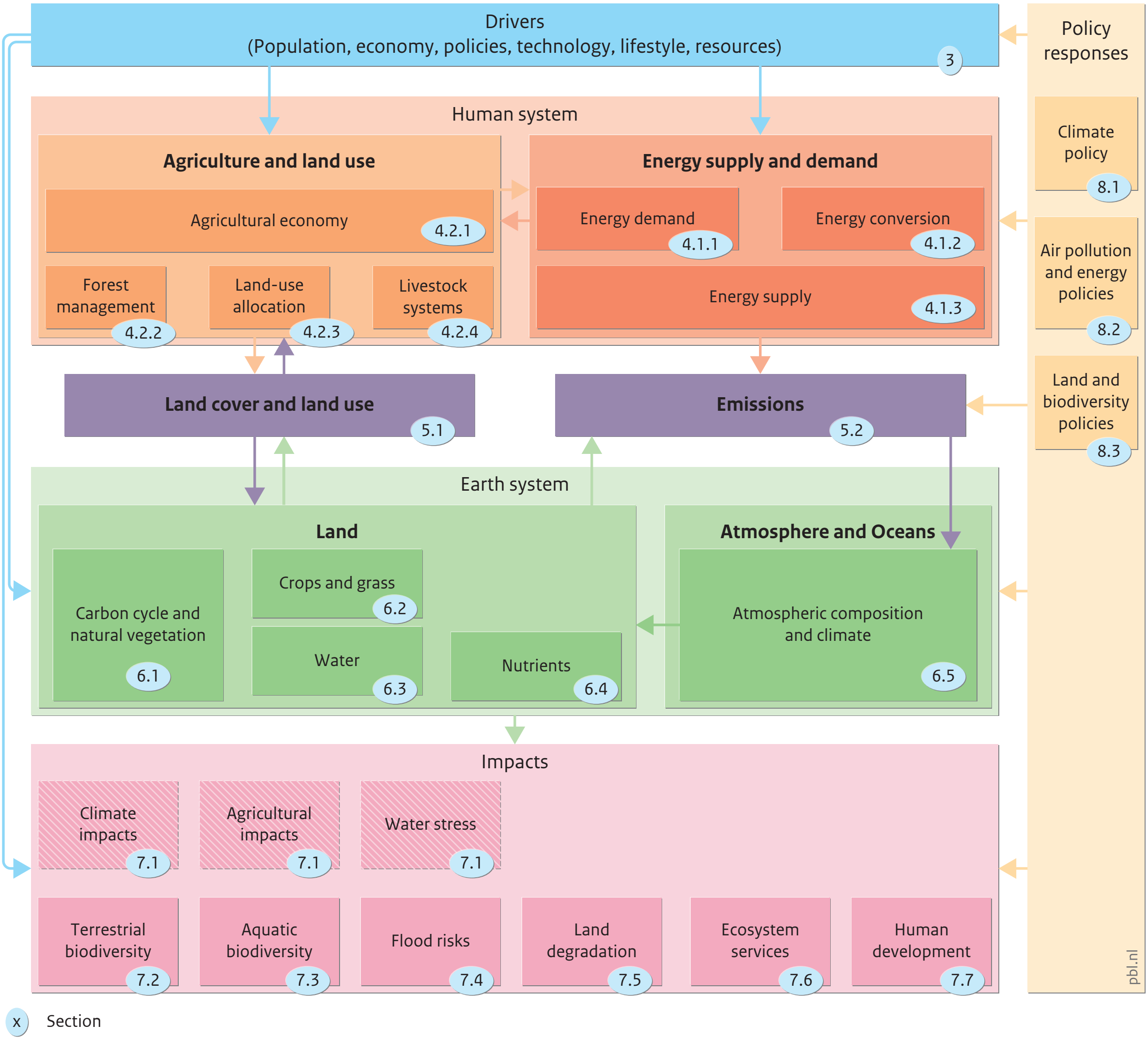
- All model components presented in Figure 1 are described in respective Sections of Chapters 3 to 8, and can be read separately.

- Each model component is described as follows: 1) Introduction, 2) Model description, 3) Policy issues, and 4) Data, uncertainties and limitations, 5) Key publications and 6) Input/Output Table. Figures include a model flow diagram, baseline results, and results for one or several policy interventions.

- The results illustrate the type of studies that can be carried out with IMAGE. They are based on recent IMAGE assessments, and as far as possible taken from peer-reviewed literature or published PBL reports. Thus, the underlying baselines may vary throughout the book.

- The content of this book is presented on the IMAGE website (www.pbl.nl/image), where additional information and model updates can be found. This website also contains a user interface to view IMAGE scenario results.

Figure 1
IMAGE 3.0 framework



Source: PBL 2014

Dark-coloured boxes refer to model components with section reference. Impacts are calculated in model components shown in the lower box, and also inside the Human system and Earth system (see Section 7.1).

Contents

Preface

The IMAGE suite of models, run by PBL, is a dynamic integrated assessment framework to analyse global change. IMAGE allows us to look into the future and helps to identify and map out major challenges ahead. A more balanced interaction between human development and the natural system is needed. IMAGE supports policymakers to address major transitions regarding the use of energy, land and water.

The version of IMAGE presented here represents the result of many years of development. The first, single-region version of IMAGE focused on climate change and was developed in the late 1980s. Since then, updates and extensions, as presented in several publications, have culminated in this latest incarnation, the IMAGE 3.0 framework. IMAGE is now better equipped to analyse, among other things, water-related issues. IMAGE can be used as a tool to construct long-term scenarios and is often deployed to feed policy analysis. The modelling framework and the results have provided core input for major international assessments and scenarios studies, such as the *Intergovernmental Panel on Climate Change* (IPCC), the *Global Environment Outlooks* (GEOs) by the United Nations Environment Programme (UNEP) and the *OECD Environmental Outlooks*.

The purpose of this publication is to elucidate both the model's current structure and how it can be applied in scenario development and policy analysis. Input assumptions and data, model functionality and impact indicators are described and illustrated by examples from recent work. The same documentation, in a more dynamic way, can also be found on the new IMAGE website (www.pbl.nl\image).

This new version of IMAGE may be 'grown up', retirement is still way beyond our horizon. There is a constant drive to extend and improve the model framework in order to address emerging policy questions. With increasing public awareness of key sustainability challenges, the focus is moving away from identifying problems towards assessment of solutions and policy responses. This publication offers valuable stepping stones towards better facilitating well-founded scientific analyses, supporting a transition towards global sustainable development. The IMAGE update secures the framework's value for the coming years, and thus the position of IMAGE as one of the leading frameworks for integrated assessment.

Over the years, many people have contributed to the development of IMAGE. PBL is indebted to all of them.

Maarten Hajer
Director-General
PBL Netherlands Environmental Assessment Agency

INTRODUCTION

1 Introduction

Tom Kram, Elke Stehfest, Detlef van Vuuren, Lex Bouwman

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1.1 Setting the stage

Background

The IMAGE 3.0 framework addresses a set of global environmental issues and sustainability challenges. The most prominent are climate change, land-use change, biodiversity loss, modified nutrient cycles, and water scarcity. These highly complex issues are characterised by long-term dynamics and are either global issues, such as climate change, or manifest in a similar form in many places making them global in character. Typically, these global environmental issues have emerged as human societies have harnessed natural resources to support their development, for instance to provide energy, food, water and shelter.

Economic growth and increasing wealth have brought enormous benefits to human societies but have been accompanied by large-scale changes to the global environment system. These changes result from clearing land, burning biomass, domesticating animals and developing crop production systems, and from human activities that have lead to emissions of air pollutants and greenhouse gases. Mankind's influence on the state and functioning of the natural environment has steadily increased in degree and spatial scale over the last 150 years.

Science now recognises humans as a geological force (Zalasiewicz et al., 2010) and suggests that the most recent age should be called the Anthropocene, a man-made era. In the last decades, concern has been growing that the scale of human interaction with the natural environment is reaching levels that could have consequences for the Earth's capacity to continue supporting an increasing population. For example, the risk that emissions and atmospheric build-up of greenhouse gases from the use of fossil fuels and from other sources will seriously affect global climate.

Key policy challenges are how to avoid or reduce current and future tension between human activity and natural systems. This requires understanding the present 'state-of-the-world' as a result of the main drivers in the past. It is also essential to explore how the world could unfold in the future and the implications for human development, including how degradation of natural systems influences opportunities for human development. Then, alternative pathways can be identified, and their merits and downsides assessed to guide policy-making.

To understand these complex, global and long-term issues, and to design effective response strategies, integrated assessment models such as IMAGE 3.0 have been developed. Integrated assessment models cover key processes, ranging from human activities as the primary drivers, to the behaviour of the natural system, and impacts on the natural environment and on human development.

Integrated environmental assessment
Integrated assessment models (IAMs) have been developed to describe the key processes in the interaction of human development and the natural environment. IAM methods and tools draw on functional relationships between activities, such as provision of food, water and energy, and the associated impacts. Traditionally, most IAMs focused on climate change and air pollution. More recently, these models have been expanded to assess an increasing number of impacts, such as air and water quality, water scarcity, depletion of non-renewable resources (fossil fuels, phosphorus), and overexploitation of renewable resources (fish stocks, forests). IAMs are designed to provide insight into how driving factors induce a range of impacts, taking into account some of the key feedback and feed-forward mechanisms. To achieve this effectively, IAMs need to be sufficiently detailed to address the problem, yet simple enough to be applicable in assessments, including exploration of uncertainties, and without loss of transparency because of the complex relationships involved (see Section 1.2).

Objective and scope of IMAGE
IMAGE is a comprehensive integrated modelling framework of interacting human and natural systems. Its design relies on intermediate complexity modelling, balancing level of detail to capture key processes and behaviour, and allowing for multiple runs to explore aspects of sensitivity and uncertainty of the complex, interlinked systems (see Section 1.5).

The objectives of IMAGE are as follows:
- To analyse large-scale and long-term interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
- To identify response strategies to global environmental change based on assessment of options for mitigation and adaption;
- To indicate key interlinkages and associated levels of uncertainty in processes of global environmental change.

IMAGE is often used to explore two types of issues:
- How the future unfolds if no deliberate, drastic changes in prevailing economic, technology and policy developments are assumed, commonly referred to as baseline, business-as-usual, or no-new-policy assessment;
- How policies and measures prevent unwanted impacts on the global environment and human development.

The baseline scenario is used to assess the magnitude and relevance of global environmental issues and how they relate to human activities. This is important at the beginning of a policy cycle when an environmental issue arises. The scenario can be used to explore how the future might unfold under business-as-usual, and to assess the costs and foregone opportunities of policy inaction, and to study the impacts on the natural environment of a human development pathway with essentially unaltered practices. To some degree, impacts may be taken into account in an endogenous feedback loop by the integrated assessment procedure. For instance, changes in temperature and precipitation resulting from climate change have an effect on agricultural productivity and water availability. Biophysical feedbacks of this type are part of the IMAGE model, see Chapters 4 to 8.

Often, alternative scenarios explore possible solutions to a problem, such as climate change, by assuming societal and policy responses to the impacts projected under baseline conditions. To this end, alternative cases are developed and implemented in model compatible terms to test how the outcomes change. They also reveal synergies and trade-offs between policy issues. For example, with increasing crop yields, less land is required to grow a given amount of crops, and thus loss of natural areas is reduced to the benefit of ecosystems rich in biodiversity. Carbon emissions from land use are also reduced when less land is converted to agriculture, but fertiliser application may increase to sustain the higher yields with emissions to air, groundwater and surface water as a consequence. Furthermore, higher yields may contribute to lower food prices and thus to reducing undernourishment and hunger to the benefit of human health.

IMAGE in comparison to other IAMs

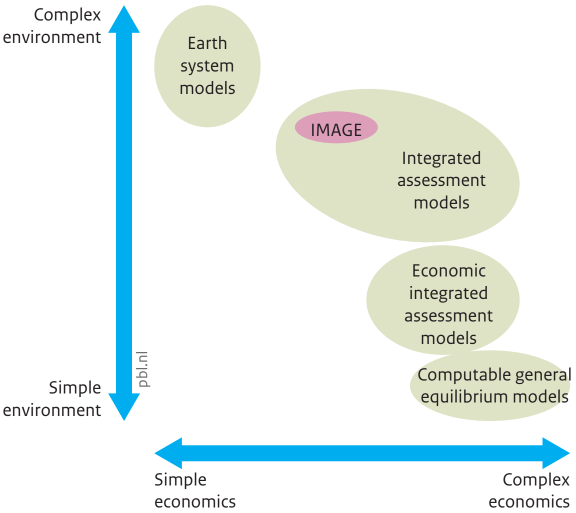
Various types of IAMs have been developed, evolving from different classes of models with a specific disciplinary focus and point of entry. These are discussed briefly in order to identify the position of IMAGE in relation to other IAM models. The common feature of all IAM models is that they all describe a combination of the Human and Earth systems to gain better understanding global environmental problems.

As indicated above, a key trade-off in IAMs is detail versus simplification. Sufficient detail is required to include all relevant processes in both the Human and the Earth system according to state-of-the-art knowledge. Simplicity is needed to ensure sufficient transparency in complex model systems, and to explore uncertainties. For instance, a crop growth model with data input on observed, local climate, soil layers and crop variety parameters may perform well at field scale. However, such a model is less suitable for use in an IAM that requires more generic crop growth representation operating as part of a global scale system. Another limitation to the level of detail captured in IAMs is the lack of consistent and complete datasets with global coverage.

While models are developed for different purposes, and thus have limited overlap in scope and detail, in practice many hybrid models are in use. As illustrated in Figure 1.1, IAM models are between models with a primary focus on the Earth system (Earth System Models) and models that focus on the Human system such as pure economic models.

Within the IAM group clearly different model groups exists, and IMAGE is characterised by relatively detailed biophysical processes and a wide range of environmental indicators. IMAGE 3.0 also includes an economic model to represent the agricultural

Figure 1.1
Different types of global models distinguished according to level of detail



Source: PBL 2014

IAM models and other models with global coverage differ in their level of detail on economic aspects (horizontal) and biophysical/technical aspects (vertical).

system, and a process model to describe the energy system, but has less detail on economics and policy instruments than other energy models. In terms of application, many models are designed and used for climate policy analysis, such as FUND and DICE, while other models address a broader range of issues. IMAGE was originally designed to assess the global effect of greenhouse gas emissions and now covers a broad range of environmental and sustainability issues.

Another reason for differences between IAM models is their history. Many have evolved from technical process models of energy systems to cover environmental issues, such as air pollution and more frequently also climatic change. Technical process models describe the physical flows of energy from primary resources through conversion processes, and transport and distribution networks to meet specific demands for energy carriers or energy services. The costs associated with the various components are tracked, and relative costs of competing technologies and supply chains determine market share. In fact, one example embedded in the IMAGE framework is the TIMER energy model (Section 4.1).

Other IAMs have their roots in economics and have evolved from models assessing the production of economic outputs to contribute to consumer utility by allocating input factors, such as capital, labour and increasingly also energy, materials and natural resources. Substitution between sectors, inputs and commodities produced depends on their relative prices, taking into account policy interventions, such as taxes and subsidies, import regulations and other market and non-market instruments. Economic models include the OECD model ENV-Linkages and the model MAGNET. The latter has been integrated into IMAGE 3.0 (see Section 4.2.1). While economic models account for consistency between economic sectors, these models tend to treat the economy in terms of material flows, biochemical, physical and ecological processes in a stylised way, which limits their capacity to capture feedback mechanisms of the natural system.

Finally, IAMs can also be distinguished by the level of geographic detail in land-based activities. To address geographical distribution of bio-geochemical and bio-geophysical processes in conjunction with human development, the IMAGE framework has been developed with a high level of geographic detail. IMAGE provides a relatively high level of detail on land-based processes, such as water, carbon and nutrient cycles, and derived indicators for biodiversity loss and flood risks, also in temporal and spatial resolution.

1.2 IMAGE 3.0 in a nutshell

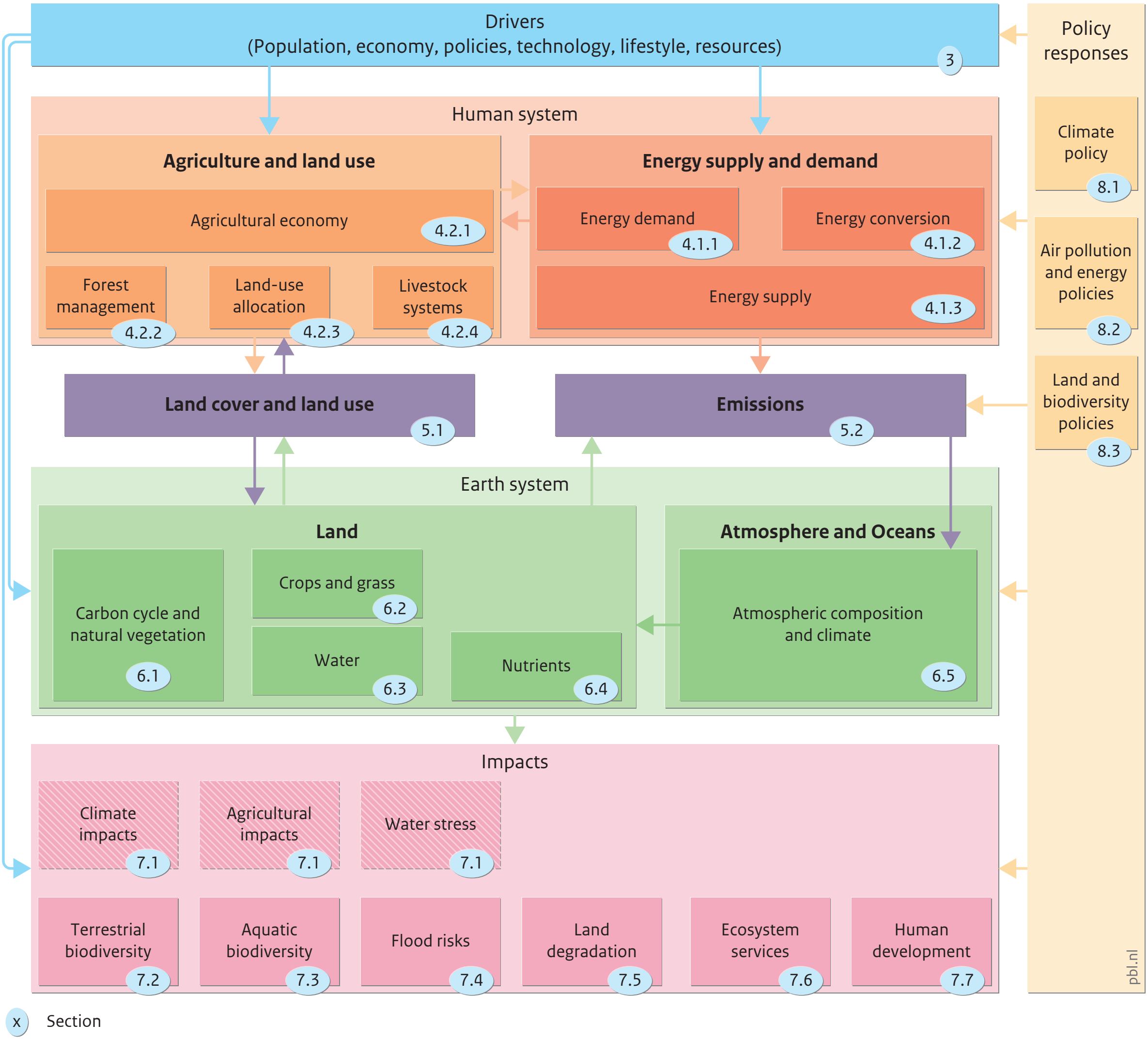
IMAGE 3.0 is a comprehensive integrated modelling framework of interacting human and natural systems. The model framework is suited to large scale (mostly global) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development.

The model identifies socio-economic pathways, and projects the implications for energy, land, water and other natural resources, subject to resource availability and quality. Unintended side effects, such as emissions to air, water and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections.

IMAGE has been designed to be comprehensive in terms of human activities, sectors and environmental impacts, and where and how these are connected through common drivers, mutual impacts, and synergies and trade-offs. IMAGE 3.0 is the latest version of the IMAGE framework models, and has the following features:

– Comprehensive and balanced integration of energy and land systems was a pioneering feature of IMAGE. Recently, other IAMs have been developed in similar directions and comprehensive IAMs are becoming more mainstream.

Figure 1.2
IMAGE 3.0 framework



Source: PBL 2014

Dark-coloured boxes refer to model components with section reference. Impacts are calculated in model components shown in the lower box, and also inside the Human system and Earth system (see Section 7.1).

- Coverage of all emissions by sources/sinks including natural sources/sinks makes IMAGE appropriate to provide input to bio-geochemistry models and complex Earth System Models (ESMs).
- In addition to climate change, which is the primary focus of most IAMs, the IMAGE framework covers a broad range of closely interlinked dimensions. These include water availability and water quality, air quality, terrestrial and aquatic biodiversity, resource depletion, with competing claims on land and many ecosystem services.
- Rather than averages over larger areas, spatial modelling of all terrestrial processes by means of unique and identifiable grid cells captures the influence of local conditions and yields valuable results and insights for impact models.
- IMAGE is based on biophysical/technical processes, capturing the inherent constraints and limits posed by these processes and ensuring that physical relationships are not violated.
- Integrated into the IMAGE framework, MAGICC 6.0 is a simple climate model calibrated to more complex climate models. Using downscaling tools, IMAGE scales global mean temperature change to spatial patterns of temperature and precipitation changes, which vary between climate models.
- Detailed descriptions of technical energy systems, and integration of land-use related emissions and carbon sinks enable IMAGE to explore very low greenhouse gas emissions scenarios, contributing to the increasingly explored field of very low climate forcing scenarios.
- The integrated nature of IMAGE enables linkages between climate change, other environmental concerns and human development issues to be explored, thus contributing to informed discussion on a more sustainable future including trade-offs and synergies between stresses and possible solutions.

Model components

The components of the IMAGE framework are presented in Figure 1.2, which also shows the information flow from the key driving factors to the impact indicators. An overview of the model components is provided in Chapter 2, and the components are described in Chapters 3 to 8.

Future pathways or scenarios depend on the assumed projections of key driving forces. Thus, all results can only be understood and interpreted in the context of the assumed future environment in which they unfold.

As a result of the exogenous drivers, IMAGE projects how human activities would develop in the Human system, namely in the energy and agricultural systems (see Figure 1.2). Human activities and associated demand for ecosystem services are squared to the Earth system through the 'interconnectors' Land Cover and Land Use, and Emissions (see Figure 1.2).

Assumed policy interventions lead to model responses, taking into account all internal interactions and feedback. Impacts in various forms arise either directly from the model, for example the extent of future land-use for agriculture and forestry, or the average global temperature increase up to 2050. Other indicators are generated by activating additional models that use output from the core IMAGE model, together with other assumptions to estimate the effects, for example, biodiversity (GLOBIO; see Sections 7.2 and 7.3) and flood risks (see Section 7.4).

Currently, impacts emerging from additional models do not influence the outcome of the model run directly. The results obtained can reveal unsustainable or otherwise undesirable impacts, and induce exploration of alternative model assumptions to alleviate the problem. As the alternative is implemented in the linked models, synergies and trade-offs against other indicators are revealed.

To apply IMAGE 3.0, all model settings are adjusted so that the model reproduces the state-of-the-world in 2005. The model calculates the state in 2005 over the period starting in 1970, using exogenous data to calibrate internal parameters. From 2005 onwards, a range of model drivers rooted in more generic narratives and scenario drivers must be prepared either by experts or teams at PBL or in partner institutes to provide inputs, such as population and economic projections. For more information on drivers, see Chapter 3. These steps are taken in consultation with stakeholders and sponsors of the studies, and with project partners.

An IMAGE run produces a long list of outputs representing the results of the various parts of the framework, either as end indicator or as intermediate inputs driving operations further downstream. Together the outputs span the range from drivers to pressures, states and impacts.

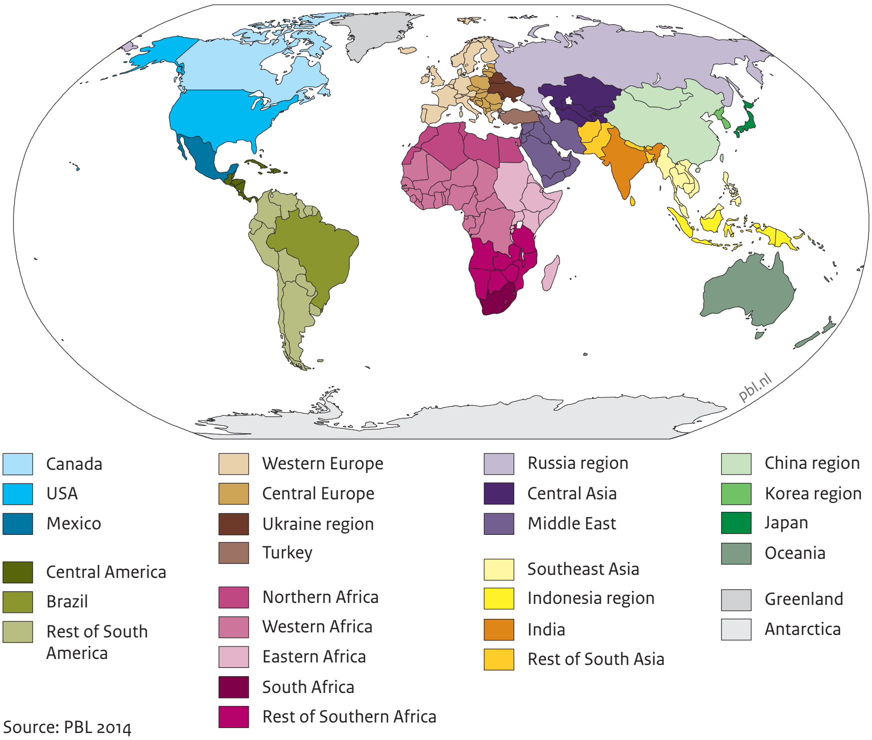
The IMAGE 3.0 model has a wide range of outputs, including:
- energy use, conversion and supply;
- agricultural production, land cover and land use;
- nutrient cycles in natural and agricultural systems;
- emissions to air and surface water;
- carbon stocks in biomass pools, soils, atmosphere and oceans;
- atmospheric emissions of greenhouse gases and air pollutants;
- concentration of greenhouse gases in the atmosphere and radiative forcing;
- changes in temperature and precipitation;
- sea level rise;
- water use for irrigation.

These standard outputs are complemented with additional impact models with indicators for biodiversity, human development, water stress, and flood risks.

Spatial resolution

While IMAGE is designed to address global issues, impacts and challenges tend to occur at different geographic scales and to different degrees in different parts of the world.

Figure 1.3
The 26 world regions in IMAGE 3.0



Source: PBL 2014

This depends on location-specific biophysical conditions, and on the level of human development (for example high income, industrialised versus low income, subsistence agriculture dominated regions, and all levels in between). It implies that indicators at the level of global totals or global averages are rarely adequate to reveal the real problems. Furthermore, policy interventions and governance structures are not uniform across scales and administrative entities, and are bound by cultural and political history.

To capture spatial and multi-scale differences, IMAGE models socio-economic developments in 26 world regions (see Figure 1.3). Land use, land cover, and associated biophysical processes are treated at grid level to capture local dynamics. The grid size has been reduced to 5x5 arcminutes in IMAGE 3.0 (corresponding to 10x10 km at the equator), from 30x30 arcminutes (0.5x0.5 degrees) in IMAGE 2. Operating within global boundaries, the regional approach provides insight to identify where specific problems manifest, where the driving factors are concentrated, and how changes in some regions influence other regions.

Areas of application

An integrated framework, such as IMAGE 3.0, covers a wide range of components of the Human and Earth systems, and contains variables in many domains. Development and applications of the IMAGE framework focus on two interrelated clusters: energy and climate; and food, land, water and biodiversity.

There are many relationships between these two clusters in IMAGE. For instance, climate change has impacts on agriculture and nature, land use for bioenergy has implications for food prices, and water for irrigation competes with water for coolant in electric power plants. Synergies and trade-offs are interesting from the perspective of policy discussions with regard to the complicating effects of unintended and often undesirable impacts. IMAGE 3.0 has the capacity to generate a long and widely diverging set of indicators for different sectors and regions.

Modular structure

Over the years, various components of the IMAGE framework have been replaced by expert models developed outside IMAGE, which can be used either as stand-alone models or within the IMAGE framework.

The **IMAGE 3.0 core model** comprises most processes in the Human system, the Earth system and their connectors Land cover/Land use and Emissions, and parts of the impacts (see Figure 1.2). This core model consists of IMAGE/TIMER energy and IMAGE/Land&Climate. The latter also includes the LPJmL model, which is an essential component of any IMAGE model run, representing carbon, water, crop and vegetation dynamics.

The **IMAGE 3.0 framework** contains other models that are employed to generate impacts (such as, GLOBIO, GLOFRIS and GISMO), and models that describe parts of the Human system, such as agro-economic models (MAGNET and IMPACT) to project future agricultural production requirements. Furthermore, policy models, such as FAIR, are used in exploring effectiveness, efficiency and equity of climate policy regimes, and to provide input on emission constraints and price signals arising from climate policy proposals (see Figure 1.2).

1.3 A brief history of IMAGE

IMAGE 3.0 is the most recent, operational version of the model framework progressively developed since in 1980s. Over the years the model was enhanced and extended continuously through incremental changes, and more profound revisions.

IMAGE 1.0

IMAGE 1.0 (Rotmans, 1990) was developed as a single region, integrated global model to explore interactions between human activities and future climate change. As one of the first Integrated Assessment Models to address climate change, IMAGE contributed to raising awareness of the long-term consequences of human development. In the absence of regional or spatially explicit algorithms, the model operated on trends in global total and average parameters, such as world population and averaged emission factors per unit of activity.

IMAGE 2.0 to 2.2

In the 1990s, the new generation IMAGE 2 was developed with regional drivers of global change and gridded, process-oriented modelling of the terrestrial biosphere, land cover and land use (Alcamo, 1994). IMAGE 2.0 comprised three subsystems:

- 13-region Energy-Industry System (EIS);
- Terrestrial Environment System (TES) operating at regional and at 0.5x0.5 degrees grid-scale;
- Atmosphere-Ocean System (AOS) to compute the resulting changes in the composition of the atmosphere leading to climate change.

Further refinements and extensions were implemented in IMAGE 2.1 (Alcamo et al., 1998) to enhance model performance and broaden its applicability to issues other than climate change.

The enhanced capabilities of IMAGE 2.2 were demonstrated in the contribution to the IPCC Special Report on Emissions Scenarios (IMAGE-team, 2001). The earlier zonal-mean climate-ocean model was replaced by a combination of the MAGICC climate model and the Bern ocean model. The resulting global average temperature and precipitation changes were scaled using temperature and precipitation patterns generated by complex Global Circulation Models (GCMs) to provide spatially explicit climate impacts and feedback. For economy and energy, the EIS of version 2.0 was replaced with the TIMER energy model, which also improved linkage with the macro-economic model Worldscan.

IMAGE 2.4

A range of developments were implemented stepwise in intermediate versions, leading to the release of IMAGE 2.4 (MNP, 2006). In close cooperation with the agro-economic research institute LEI, links were established with agro-economic modelling in IMAGE 2.4. This ensured the inclusion of biophysical conditions in modelling future agricultural production based on intensification of production and expansion of agricultural area.

Furthermore, to align closer with policy discussions, the number of regions was increased to 24 to reveal the position of major global players. Other extensions included a link with the global biodiversity model GLOBIO to study impacts of global change drivers on natural and cultivated land.

Many of the components were enhanced, including the energy model TIMER, emission modelling and the carbon cycle. Experimental links with an intermediate complexity climate model were discontinued and the simple climate model MAGICC with a strong feature to represent uncertainties in the climate system was adopted as the default. IMAGE 2.4 has played a key role in supporting various international environmental assessment studies.

Towards IMAGE 3.0

After publication of the IMAGE 2.4 book and a subsequent progress review by the IMAGE Advisory Board, the framework has been further developed. These developments were published in journal articles and conference papers, but no new versions were officially released. For example, representation of energy demand was improved by more bottom-up modelling of household energy systems in TIMER for rural and urban population by income level. Selected industries were better represented in more technical detail to underpin energy demands and emissions. The forestry sector included forestry management options in addition to clear-cutting.

In cooperation with Wageningen University (WUR) and the Potsdam Institute for Climate Impact Research (PIK, Germany), the IMAGE natural vegetation and crop components were replaced with the LPJmL Global Dynamic Vegetation Model. This enabled modelling of linked carbon and water cycles, and adding a global hydrology module to IMAGE, which was not available in previous versions. Modelling biodiversity impacts was extended to cover freshwater systems as well as terrestrial biomes.

IMAGE 3.0

The following new developments have been incorporated in IMAGE 3.0:

- **Energy demand modules** to address household energy demand and energy carrier preferences for urban and rural populations, and per income level in developing and emerging economies. Energy demand also includes selected energy-intensive industries using technological production alternatives with their costs and efficiencies in delivering energy services.
- **Forestry management module** covering different production systems per region. Management systems include clear-cutting, selective cutting (conventional and reduced impact logging) and dedicated forest plantations. Wood products are also retrieved from areas deforested for agriculture and other purposes.
- **Plant growth and carbon modelling by LPJmL,** coupled to IMAGE. LPJmL simulates plant growth as a function of soil properties, water availability, climatic conditions and plant and crop growth parameters. Carbon stocks and fluxes, biomass yields and water surplus are integrated and internally consistent.
- **Global hydrological modelling,** linked with natural vegetation and crop growth in LPJmL. The balance of precipitation and evapotranspiration in each grid cell feeds a routing network of rivers and natural lakes. Man-made reservoirs for hydropower production, irrigation, and mixed use are included and alter river flows.

- **Nutrient (N, P) soil budgets** for natural and anthropogenic land use to assess nutrient cycles in agricultural and natural ecosystems, fertiliser use, and efficiency and integration of manure in crop production systems. In addition to these non-point sources of nutrients, point sources of urban wastewater are modelled. The fate of the nutrients in the river systems determines the load in coastal waters at a river mouth, creating risks of hypoxia and algal blooms.
- **Landscape composition on a 5x5 minutes resolution**, instead of the 0.5x0.5 degrees grid used in all IMAGE 2.x versions. Depending on the components, 5 minute information is processed either directly or translated into fractional land use at the 0.5 degree scale.
- **MAGICC 6.0**, which updates the climate model and associated data, is a simple climate model that estimates global average temperatures as the result of net greenhouse gas emissions, carbon uptake, and atmospheric concentrations of climate forcing agents. The global average temperature is used to scale grid-based climate indicators emerging from complex climate model studies.
- **Additional impact components,** providing information on aquatic biodiversity, flood risks, soil degradation, ecosystem services, and human health.
- **Optimal greenhouse gas emission reduction pathways** for overall climate policy goals are explored under assumptions for participation timing, rules and emission targets under global strategies. A cost-benefit analysis tool has been added to test the net economic outcome of mitigation efforts, adaptation costs and residual climate change impacts at different levels of forcing, subject to cost and damage assumptions found in the literature.

1.4 Organisational set-up and scientific quality

Network strategy

The IMAGE team at PBL (and predecessors RIVM and MNP) works in close collaboration with institutes and universities in the Netherlands and other countries to develop and apply the IMAGE framework. PBL coordinates and integrates IMAGE development, and works in a network to ensure scientific excellence, and to extend expertise for IMAGE beyond the resources available at PBL.

As a result of the network strategy, several expert models have been incorporated to improve and extend the IMAGE framework. For instance, the MAGNET model has been included as the agro-economic model, GLOBIO as the biodiversity model, LPJmL as the crop, carbon, and hydrology model, and CLUMondo as the land-use dynamics model.

IMAGE Advisory board

To ensure scientific quality, the IMAGE framework is subject to external review. The IMAGE Advisory Board reviews each new release of the IMAGE model on scientific rigor and quality of the methods and data, and advises on strategic directions for further model development.

1.5 Uncertainties

Uncertainties and limitations with regard to IMAGE are described in Chapter 2 and for each IMAGE component separately in Chapters 3 to 8. Generic aspects of uncertainty in IMAGE are outlined below.

Structural key data uncertainty is due to incomplete knowledge of historical time series of model data, for example on energy demand and supply, emissions, and land use and land-use change. Other key input data, such as soil maps and temperature and precipitation maps, are uncertain, but data sets are continuously improved. This uncertainty is not addressed explicitly but the best data available are used and harmonised with other modelling teams and partners.

There is **structural and methodological uncertainty** (incomplete knowledge of relationships) in many parts of the IMAGE framework, for instance the impact of climate change on crop yields, and local climate change. This uncertainty can be addressed to some extent by alternative model formulations, such as for crop growth/natural vegetation, carbon cycle, land-use allocation, climate change (via climate sensitivity and temperature/precipitation patterns). Structural uncertainty can be also be addressed in model inter-comparison studies and other multi-model studies to compare IMAGE results with the range of outcomes from other models and with results for ranges found in literature, and to provide information on model functioning. The overall model uncertainty arising from uncertain processes and data can be assessed in systematic sensitivity analyses. This has been done, for example, on the CO_2 fertilisation factor in crop and natural vegetation growth (Brinkman et al., 2005) and for many parameters of the energy model TIMER (Van Vuuren, 2007).

Uncertainty in future scenario drivers, such as population, economic growth, and technology, is mostly addressed by exploring variants in assumed reference pathways, such as high/low variants of population projections, or by assuming contrasting future scenarios. Similarly, uncertainty in policy targets and societal trends is addressed by exploring alternative scenarios, varying one or more key input parameters, such as learning-by-doing parameters, composition of human diets, and other lifestyle choices.

A distinct source of uncertainty arises from the **level of aggregation,** with socio-economic processes represented by 26 regions, and the terrestrial biosphere modelled at 5 or 30 minute grid cells. At region and grid cell, all behaviour is average behaviour, not taking into account heterogeneity within a region (e.g., in income distribution, economy, farming systems), and at grid cell (e.g., climate, soils, and landscape composition). Major differences between countries in a world region are masked and all future trends apply to the average, although countries may develop along different pathways. Thus, land use on a country or sub-country level is possible on a 5-minute map but must be interpreted with caution.

1.6 Applications

IMAGE has been used for a variety of purposes and studies as shown in the following examples.

Input to global integrated assessments of environmental issues

- **Millennium Ecosystem Assessment (MA):** Assessment of four global scenarios on the development of ecosystem services up to 2050. The IMAGE framework was used to focus on the role of ecosystem services to support human development (MA, 2005).
- **OECD Environmental Outlook to 2030** (OECD, 2008) and the **OECD Environmental Outlook to 2050** (OECD, 2012): IMAGE was used to develop the environmental baseline according to the economic projections of the OECD economic model ENV Linkages, and to analyse selected policy intervention cases.
- **UNEP Global Environment Outlooks 3 and 4 (GEO-3 and -4):** These outlooks focused on environment for human well-being as the central theme linking environment and development. IMAGE contributed to the energy outlook, and calculated the land-use change and climate consequences of the four updated GEO scenarios (UNEP, 2002; UNEP/RIVM, 2004).
- **Roads from Rio+20:** Alternative scenarios were explored with IMAGE to reach international development and environment targets, such as halting biodiversity loss and limiting climate change (PBL, 2012). In reaching these targets, alternative pathways were assumed for globally coordinated or regionally differentiated strategies, by either relying primarily on technology solutions or combining these with changes in dominant consumer preferences and behaviour (diets, transport mode).

Global sector and topical assessments of biodiversity, climate, and energy and bioenergy

- **Global Energy Assessment (GEA):** Exploration of different normative energy futures. IMAGE was used to supplement the work presented by the MESSAGE model from IIASA (GEA, 2012).
- **Protein Puzzle:** This PBL study assessed environmental issues related to consumption and production of animal products and other protein-rich foodstuffs for the EU-27 and on a global scale. IMAGE was used to analyse options to reduce environmental impacts from animal products via changes of diets and in the supply chain (PBL, 2011).
- **Representative concentration pathways (RCPs):** IMAGE was used to develop RCP2.6 and in coordinated work related to the overall development of the RCPs (Van Vuuren et al., 2012).
- **Shared socio-economic pathways (SSPs):** Building on the RCP work, integrated assessment models including IMAGE are being used in developing Shared Socio-Economic Reference Pathways (SSPs) together with the RCPs as the backbone of

a new generation of scenarios for climate change research (Moss et al., 2010; Van Vuuren et al., 2014).
- **IPCC Assessment Reports (AR4 and AR5):** IMAGE/TIMER/FAIR were used to explore comprehensive global mitigation scenarios (Van Vuuren et al., 2007a), and IMAGE experts are contributing to the Working Group I, II, and III reports.
- **Global Nutrients from Watersheds (NEWS)**: preparation of IMAGE data on global nutrient surface balances for the UNESCO-Intergovernmental Oceanographic Committee NEWS project (Seitzinger et al., 2005; Seitzinger et al., 2010).
- **Rethinking Global Biodiversity Strategies:** Building on earlier biodiversity assessments (Alkemade et al., 2006), the IMAGE framework was used in assessing options to reduce pressure on biodiversity from human activities in addition to the more commonly applied conservation measures (PBL, 2010).

Strategic EU policy support
- **Greenhouse Gas Reduction Policy (GRP)**: IMAGE including TIMER and FAIR was used to explore climate change abatement targets and regimes in support of EU policy making (European Commission, 2005);
- **Support of international climate policy (DG Climate):** The FAIR model supported by other components of IMAGE is used to analyse international climate policy in a series of projects for DG Climate.
- **DG Environment studies:** To support strategic orientation, IMAGE was used in identifying new and emerging aspects of under-exposed problems in other world regions as a result of activities and proposed policies in the EU-27 (Kram et al., 2012). IMAGE was also used in assessing prospects for resource efficiency enhancements in the five key areas of energy, land use, phosphorus, fresh water, and fish stocks (Van den Berg et al., 2011).
- **EuRuralis:** Assessment of alternatives to the current EU Common Agricultural Policies (CAP) to support discussions on reforms by and between Member States. IMAGE was used to assess future prospects for agriculture and the rural areas in the EU-25 (Eickhout et al., 2007)

Model comparison projects
- **Energy Modelling Forum (EMF):** IMAGE has contributed to several studies, such as EMF-22 on global and regional mitigation strategies for greenhouse gas emissions, and the Asian Modelling Exercise (AME) focusing on climate emissions and mitigation in the Asian region, comprising global and regional/national model analyses.
- **AgMIP, ISI-MIP:** IMAGE was used in two model inter-comparison projects to assess climate change impacts projected by a range of models for IPCC 5th Assessment Report. Under the auspices of AgMIP and ISI-MIP, the effect of climate change on crop yields was assessed in a global gridded crop model comparison that included the new IMAGE crop model LPJmL as a stand-alone model, and GAEZ-IMAGE, the crop model in IMAGE 2.4 (Rosenzweig et al., 2013). The AgMIP comparison of

agro-economic models included the IMAGE agro-economic model, MAGNET (Nelson et al., 2014; Von Lampe et al., 2014).

Research

- **EU Seventh Framework Programme (FP7):** IMAGE has been used and further developed in several FP7 projects, including PEGASOS, COMBINE, RESPONSES, ADVANCE, FOODSECURE, AMPERE, LIMITS, PERSEUS, LUC4C and PATHWAYS.
- **Dutch National Science Foundation (NWO):** several PhD and Post Doc studies have been funded including **EC-IMAGE** (exploring linking IMAGE and the complex climate model EC-Earth, in cooperation with Utrecht University and the Dutch Meteorological institute KNMI); **Global Land-Use Systems** (developing a new land use dynamics model for IMAGE, with VU University Amsterdam); and **Planetary Boundaries for Fresh Water** (using IMAGE to explore the boundaries for sustainable water use in cooperation with Wageningen University).
- **Knowledge Infrastructure Sustainable Biomass (KISB)**: A joint research project of the IMAGE team, LEI and Utrecht University to explore future biomass supply, funding three PhD students.
- **Climate Changes Spatial Planning:** Dutch research project co-financed two PhD studies at Wageningen UR/Alterra on agricultural intensity (Neumann, 2010) and on upscaling crop growth modelling (Bussel, 2011). In addition, another PBL/Alterra co-funded PhD study contributed to hydrological modelling for IMAGE (Biemans, 2012).
- **PBL uncertainty analysis:** Several uncertainty analyses were carried out using the IMAGE energy model TIMER, including a systematic Monte Carlo type analysis (Van Vuuren, 2007), and experiments to identify the uncertainty related to model calibration (Van Ruijven et al., 2010b).
- **PBL research:** IMAGE was used to investigate areas of specific interest to policy makers and the wider public, such as contribution of dietary changes to climate policy (Stehfest et al., 2009), the future of aquaculture and environmental consequences (Bouwman et al., 2011; Bouwman et al., 2013b) and the potential for bioenergy and carbon capture storage (CCS), and geo-engineering as part of mitigation strategies (Van Vuuren and Stehfest, 2013).

OVERVIEW

OVERVIEW

2 Overview of IMAGE 3.0

Detlef van Vuuren and Elke Stehfest

Key policy issues

- How could global environmental issues such as climate change, biodiversity loss and air pollution evolve?
- What are the consequences of these changes for international targets for biodiversity protection (addressed by the CBD), climate change (UNFCCC) and human development (addressed by the Millennium Development Goals and Sustainable Development Goals)?
- How could response strategies limit environmental pressures and foster more sustainable development?
- What are the linkages between environmental change and human development? What are key uncertainties?

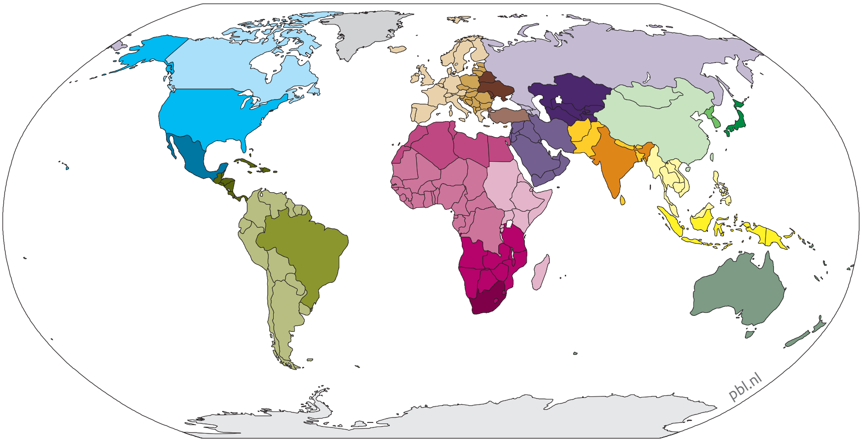
2.1 Introduction

Integrated assessment models, such as the IMAGE framework, are established as powerful tools in assessing complex, large-scale environmental and sustainable development issues. As many of these issues are closely interlinked, integrated models are needed to analyse the consequences of these linkages, and the substantial inertia in the human-environment system can only be captured in long-term scenarios. Here, an overview of the IMAGE framework and its use in assessing long-term environmental and human future is presented.

2.2 Model description

The IMAGE framework is structured according to the causal chain of key global sustainability issues (see Figure 1.2). IMAGE comprises two main systems. The *Human or socio-economic system* describes the long-term development of human activities relevant for sustainable development. The *Earth system* describes changes in the natural environment. The two systems are linked by the impacts of human activities on the Earth system, and by the impacts of environmental change in the Earth system on the Human system.

Figure 2.1
The 26 world regions in IMAGE 3.0



Source: PBL 2014

1. Key features of IMAGE

Spatial scale

The Human system and the Earth system in IMAGE 3.0 are specified according to their key dynamics. The geographical resolution for socio-economic processes is 26 regions defined based on their relevance for global environmental and/or development issues, and the relatively high degree of coherence within these regions (Figure 2.1). In the Earth system, land use and land-use changes are presented on a grid of 5x5 minutes, while the processes for plant growth, carbon and water cycles are modelled on a 30x30 minutes resolution.

Temporal scale

The Human system and the Earth system each run at annual or five-year time steps focusing on long-term trends to capture inertia aspects of global environmental issues. In some IMAGE model components, shorter time steps are also used, for example, in water, crop and vegetation modelling, and in electricity supply. The model is run up to 2050 or 2100 depending on the issues under consideration. For instance, a longer time horizon is often used for climate change studies (see Section 1.6). IMAGE also runs over the historical period 1971-2005 in order to test model dynamics against key historical trends.

2. Modular structure

IMAGE has been set-up as an integrated assessment framework in a modular structure, with some components linked directly to the model code of IMAGE, and others connected through soft links (the models run independently with data exchange via data files). This architecture provides more flexibility to develop components separately and to perform sensitivity analyses, recognising that feedback may not always be strong enough to warrant full integration. For example, the various components of the Earth system are fully linked on a daily or annual basis. However, components of the Human system, such as the TIMER energy model and the agro-economic model MAGNET, are linked via a soft link, and can also be run independently.

The IMAGE core model comprises most parts of the Human system and the Earth system, including the energy system, land-use, and the plant growth, carbon and water cycle model LPJmL. The IMAGE framework includes soft-linked models, such as the agro-economic model MAGNET, and PBL policy and impact models, such as FAIR (climate policy), GLOBIO (biodiversity), GLOFRIS (flood risks) and GISMO (human development).

Below, the various components of the IMAGE system are described briefly, and in further detail in the subsequent chapters. Results from the Rio+20 study (PBL, 2012, see Box 2.1) and some other studies are used in this chapter to illustrate the main model output.

Box 2.1: The Rio+20 study
Using the IMAGE model, the PBL study Rio+20 (PBL, 2012) assessed pathways to achieve ambitious global sustainability targets in 2050, including limiting climate change to 2 °C, stabilising biodiversity loss and providing full access to energy, water and food. The baseline scenario assessed possible development without major changes in current policies. Three alternative scenarios assessed possible routes to achieving the sustainability targets. The first scenario (Global Technology) was directed to achieving the target mainly through large-scale introduction of advanced technologies. The second scenario (Decentralised Solutions) assessed achieving the long-term targets by introducing small-scale technologies and emphasising local-scale solutions. The third scenario (Consumption Change) focused on the role of lifestyle changes in achieving the targets. In this chapter, the Rio+20 study is used to illustrate potential assessments with IMAGE.

3. Drivers (population, economy, policies, technology)

Key model inputs are descriptions of the future development of so-called direct and indirect drivers of global environmental change. These include population, economic development, lifestyle, policies and technology change (Chapter 3). Most drivers such as technology change are input in various IMAGE components (see Table 3.1). To ensure that exogenous assumptions about these factors are consistent, brief scenario story-lines are formulated on how the future may unfold and are used to derive internally consistent assumptions for main driving forces. For example, yield assumptions in the agricultural economy model and performance of solar power production in the energy model depend on a more generic description of the rate of technology change. Population and economic development can be provided as quantitative outputs from external sources or models, and dealt with quantitatively as exogenous model drivers. Other drivers mostly concern assumptions in other parts of IMAGE.

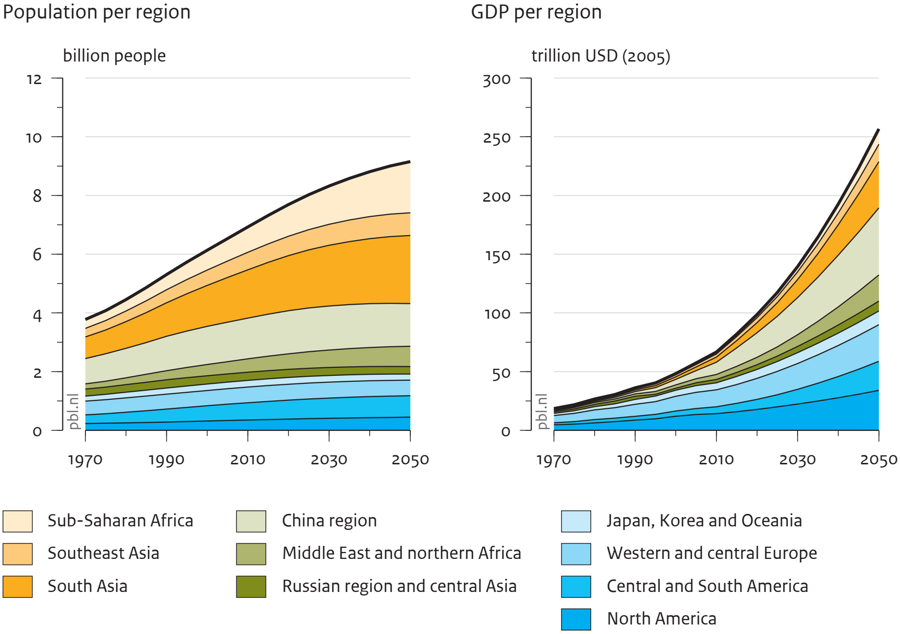
For population, IMAGE uses exogenous assumptions, such as total population per region, household size and urbanisation rate. However, GISMO population projections can also be used, which enable feedback of environmental factors, such as air pollution and undernourishment on population growth to be taken into account (Section 7.7). Exogenous assumptions are used for economic variables, such as GDP. In most studies, economic projections are developed by macro-economic models based on the scenario storylines. Sector-specific economic indicators and household consumption can be derived directly from such models, and complemented by income categories, reflecting the GINI coefficient, a measure of disparity in income distribution.

Example: In the Rio+20 study (PBL, 2012), global population is based on the UN medium projection and grows to about 9 billion people in 2050, the increase occurring mostly in developing countries (Figure 2.2). The economic projection of the Rio+20 study shows that developing countries increasingly dominate the world economy in terms of total GDP (Figure 2.2). For the OECD countries, the baseline scenario assumes a long-term economic growth rate of 1 to 2% per year over the whole scenario period. In the short term, per capita growth rates in Asia and Latin America are much higher, but converge gradually to a long-term growth rate of around 2% per year. In contrast, Africa shows a later peak in economic growth.

4. The Human system: Energy supply and demand and agricultural systems

Human activities that play a key role in environmental and sustainable development issues are energy use and supply (Section 4.1) and food consumption and supply (Section 4.2).

Figure 2.2
Global demographics and economic growth under the baseline scenario



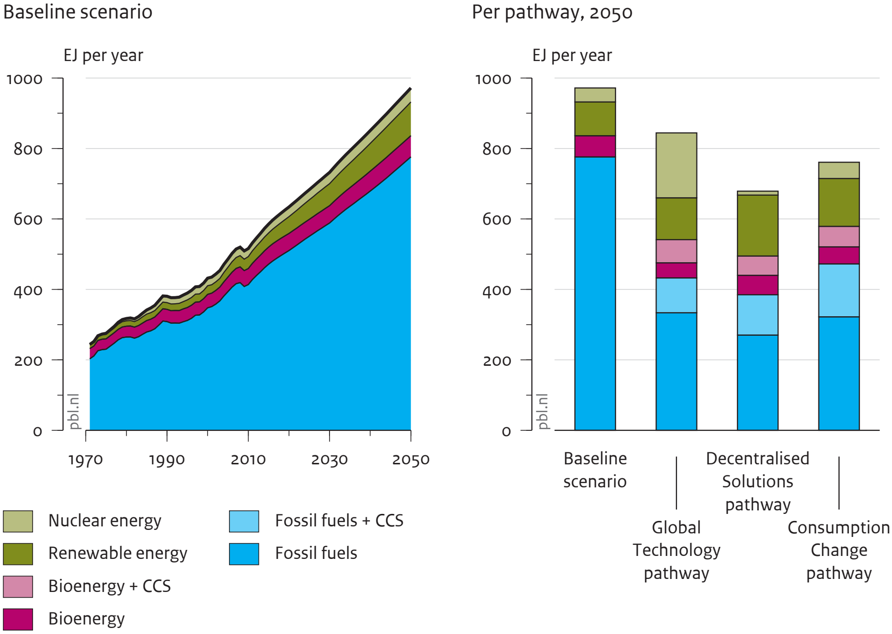
Source: PBL 2012

Energy demand and supply
The IMAGE framework uses the detailed energy system model "The IMage Energy Regional model" (TIMER) to describe the long-term dynamics of the energy system (Sections 4.1.1 to 4.1.3). The model includes a description of demand for energy services and end-use energy carriers, and also describes the future role of fossil fuels versus alternative supply options, such as renewables and nuclear power to meet the demands.

The model determines demand for energy services with population and income as primary drivers and assumptions on lifestyle. Demand is met by final energy carriers, which are produced from primary energy sources. The mix of final energy carriers and the technologies to produce them are chosen on the basis of their relative costs. Key processes that determine these costs include technology development and resource depletion, and also preferences, fuel trade assumptions and policies.

The model output demonstrates how energy intensity, fuel costs and competing non-fossil supply technologies develop over time. Emission mitigation is generally modelled on the basis of price signals. A carbon tax (used as a generic measure of climate policy) induces additional investment in energy efficiency, and in fossil-fuel substitution,

Figure 2.3
Global primary energy supply under the baseline and sustainability scenarios

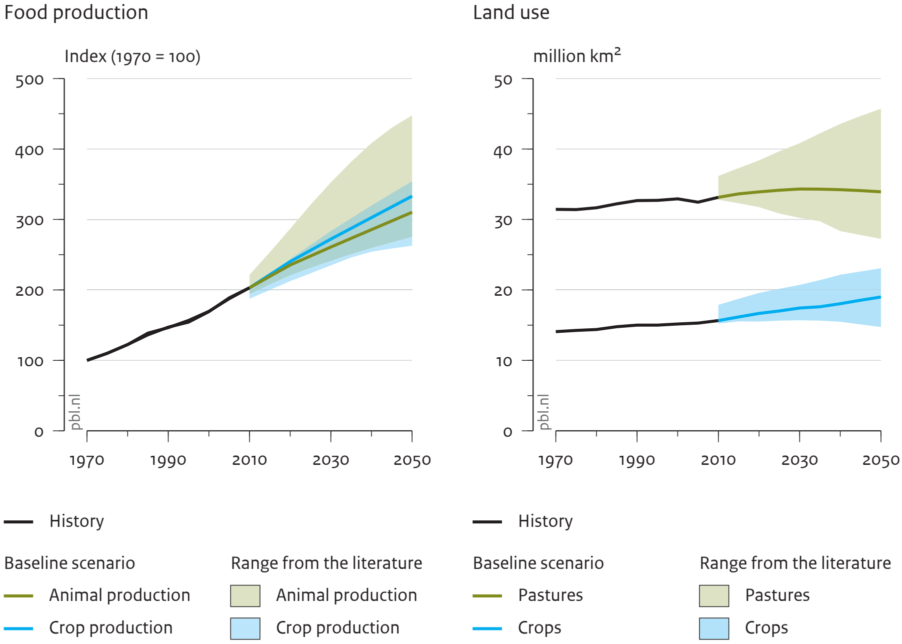


Source: PBL 2012

bioenergy, nuclear power, solar power, wind power and carbon capture and storage. The energy model is linked to other parts of IMAGE via calculated emissions and demand for bioenergy production (generating input into the land use model).

Example: The model can be used to make detailed projections of the energy system, with and without climate policy. In the Rio+20 study, the baseline scenario without climate policy projects a 65% increase in energy consumption in the 2010-2050 period, driven by continued population and economic growth. With no fundamental change in current policies, fossil fuels are expected to retain a large market share as their market price is expected to remain below the price of alternative fuels for most applications. In climate policy scenarios, the inclusion of a carbon price leads to an increased share of alternative technologies and resources, such as carbon capture and storage, nuclear power and renewables (Figure 2.3).

Figure 2.4
Global food production and land use under the baseline scenario



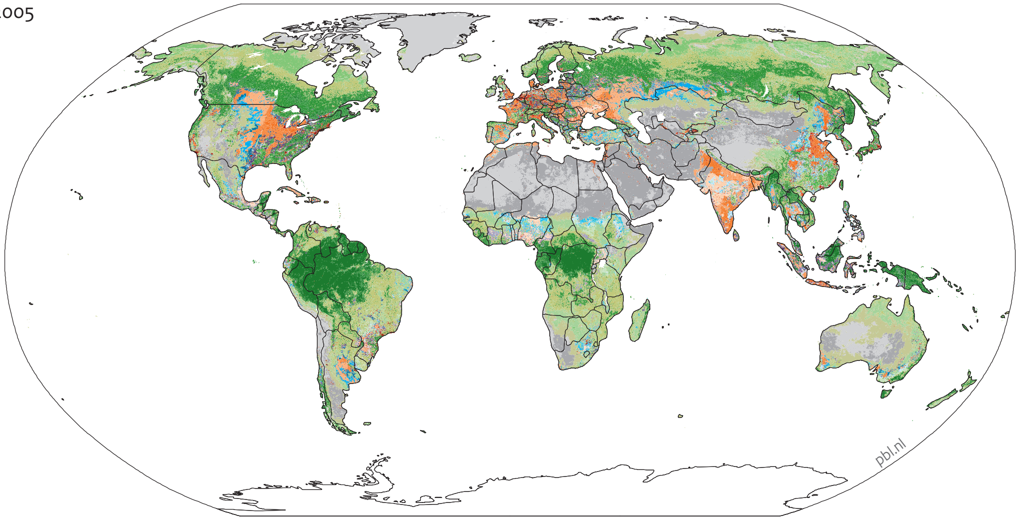
Source: PBL 2012

Food consumption and agriculture

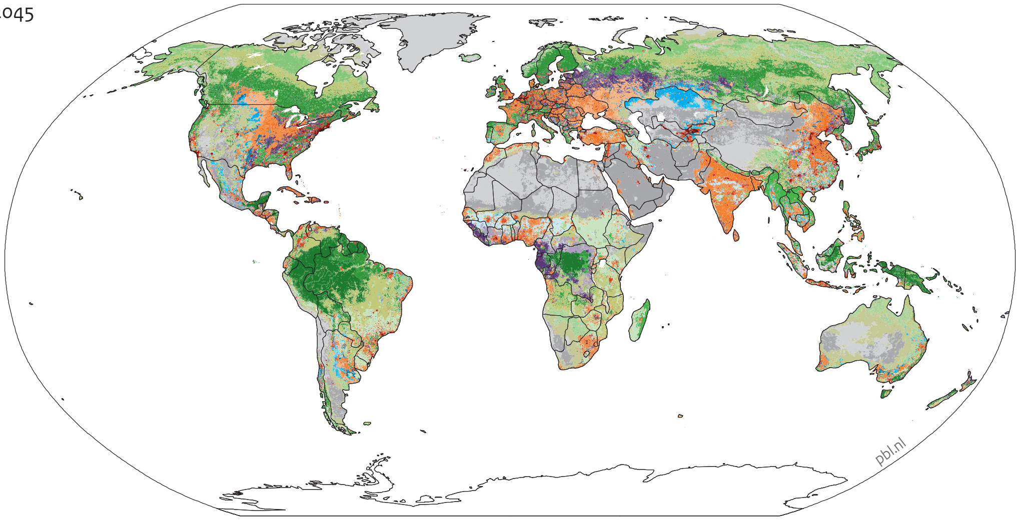
Demand for and production of agricultural products are modelled by the soft-linked agro-economic models MAGNET or alternatively IMPACT (Section 4.2.1). The IMAGE crop (Section 6.2) and land-use (Section 4.2.3) models supply information to MAGNET on land supply by region and changes in potential yields. MAGNET provides information on future agricultural production levels and intensity by region, matching regional demands through trade. MAGNET assesses production of agricultural products based on combinations of primary (land, labour, capital and natural resources) and intermediate production factors. For the livestock sector, IMAGE makes scenario-specific assumptions about livestock production in different systems (Section 4.2.4). A key purpose of the agro-economy model is to determine regional production levels and the associated yields and livestock efficiencies, taking into account changes in technology and biophysical conditions. An increase in demand for agricultural production can be met by land expansion (using the regional land supply curves) and/or intensification of land use and increasing yields. IMAGE 3.0 also calculates timber demand and forest management (Section 4.2.2).

Figure 2.5
Distribution of land systems

2005



2045



Cropland systems
- Extensive with few livestock
- Extensive with bovines, goats and sheep
- Extensive with pigs and poultry
- Medium intensive with few livestock
- Medium intensive with bovines, goats and sheep
- Medium intensive with pigs and poultry
- Intensive with few livestock
- Intensive with bovines, goats and sheep
- Intensive with pigs and poultry

Bare systems
- Bare
- Bare with few livestock

Mosaic cropland and grassland systems
- With bovines, goats and sheep
- With pigs and poultry
- Extensive; with few livestock
- Medium intensive; with few livestock
- Intensive; with few livestock

Mosaic cropland and forest systems
- With pigs and poultry
- Extensive; with few livestock
- Medium intensive; with few livestock
- Intensive; with few livestock

Settlement systems
- Peri-urban and villages
- Urban

Forest systems
- Dense
- Open with few livestock
- Open with pigs and poultry

Grassland systems
- Natural
- With few livestock
- With bovines, goats and sheep

Mosaic (semi-)natural systems
- Grassland and forest
- Grassland and bare

Source: Van Asselen and Verburg 2013, PBL 2014

2

Example: Almost all IMAGE baseline scenarios, including the Rio+20 baseline, project an increase in agricultural production driven by population growth and changes in dietary patterns associated with increasing per capita income (Figure 2.4). Consistent with historical trends, most of the increase is met by higher production per hectare (intensification). In the Rio+20 baseline, slow expansion of the agricultural area in developing countries can be observed, mainly for crops and to a lesser extent for pasture (Figure 2.4). Alternative scenarios explore ways to mitigate agricultural expansion, including the influence of enhanced yield increase, dietary changes, and reduction in post-harvest losses.

5. Interaction between the Human system and the Earth system: land cover/land use and emissions

The Human system influences the Earth system in various ways, such as land use and atmospheric emissions, but also water extraction, and water and soil pollution. The representation of key factors of land use and atmospheric emissions in the IMAGE model are discussed below.

Land cover and land use

Using demand for agricultural products, including food, feed and bioenergy, the Land-use allocation model locates production areas on a 5x5 minute grid (Section 4.2.3). A region-specific regression based suitability assessment and an iterative allocation procedure are used. Alternatively, the land-use model can also integrate CLUMondo (using a more complex allocation procedure). In most regions, the main determinants of suitability for agricultural expansion are population density, accessibility, topography, and agricultural productivity. In the model, suitability is used in combination with regional preferences for different types of production systems (determined from historical calibration) to allocate land use to the grid. In addition, the IMAGE land use and land cover module (Section 5.1) collects and combines information from the agricultural system and the Earth system to provide maps of land-use and land-cover parameters, including fertiliser input, livestock densities, rain-fed and irrigated crop fractions, bioenergy crops, and forest management.

Example: In most baseline scenarios, increased agricultural production in tropical regions leads to loss of natural ecosystems and associated biodiversity loss. Most expansion is projected to occur in highly productive ecosystems close to agricultural areas, including tropical forests and woodland, and other high nature value savannah and grassland areas. The agricultural area is contracting in temperate zones and the grid cells least suitable for production potential are abandoned. The resulting changes in land use are depicted in Figure 2.5 (see also Section 4.2.3).

Emissions
In IMAGE, emissions are described as a function of activity levels in the energy system, in industry, in agriculture and land-cover and land-use change, and they are also influenced by assumed abatement actions (Section 5.2). The model describes emissions of major greenhouse gases, and many air pollutants, calibrated to current international emission inventories. In some cases, the emission calculation uses detailed process representation on a grid (e.g., emissions from cultivated land and land-cover change) but in most cases, exogenous emission factors are used. Change in emission factors over time is estimated according to the storyline, sometimes assuming constant emission factors, but often assuming emission factors decrease over time along with economic development (consistent with the environmental Kuznets curve). Abatement of greenhouse gas emissions reflects estimates per region, sector and gas often optimised in the FAIR model (Section 8.1).

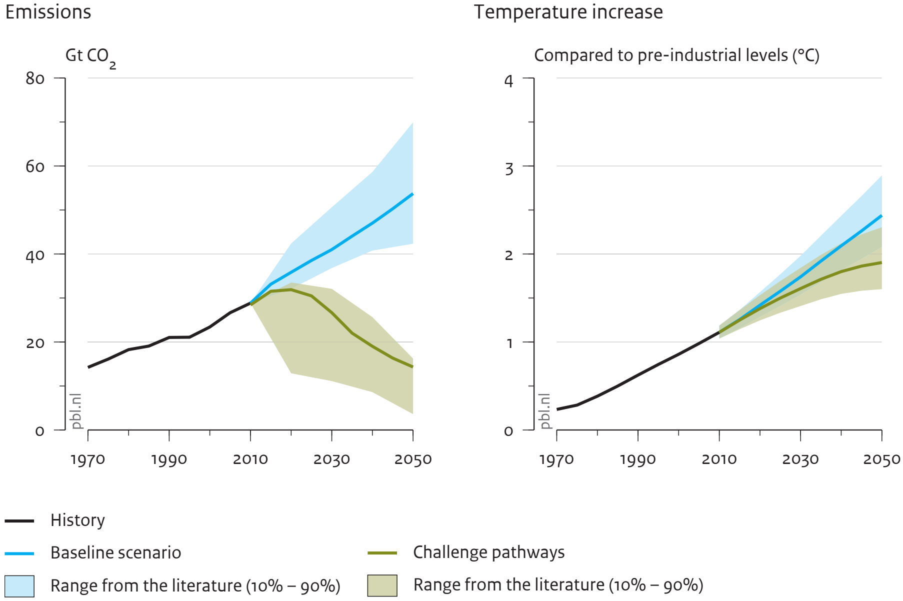
Example: In the Rio+20 baseline, increasing energy and agricultural production levels lead to an increase of associated greenhouse gas emissions (Figure 2.6). For air pollutants, the emission trends are more diverse. A decrease is projected in high-income countries, as emission factors drop faster than activity levels increase. However, in most developing country regions, increasing energy production is projected to be associated with more air pollution. In the policy scenarios, the target to keep global mean temperature change below 2 °C requires global greenhouse gas emissions to be reduced by about 50% in 2050. This is achieved in the model by structural changes in the energy system and by changes in emission and abatement factors.

Box 2.2: Downscaling as a tool to link different geographical scales
IMAGE socio-economic modelling is done on the scale of 26 world regions. However, some applications and users of IMAGE output need more detailed information. For this purpose, tools have been developed to downscale information on population, income, energy use and emissions to a 0.5x0.5 grid level (Van Vuuren et al., 2007b) and to 5x5 minute grid for population and income. Information from the Earth system is available at 0.5 degree or 5 minute resolution.

6. The Earth system

Carbon cycle, natural vegetation, crops and grass
In IMAGE 3.0, the terrestrial carbon cycle and natural vegetation dynamics (Section 6.1), and crop and grass production (Section 6.2) are modelled with LPJmL. This model is used to determine productivity at grid cell level for natural ecosystems and crops on the basis of plant and crop functional types. Key inputs to determine productivity include climate conditions, soil types and assumed technology/ management levels. The model

Figure 2.6
Global greenhouse gas emissions and temperature changes under the baseline and sustainability scenarios

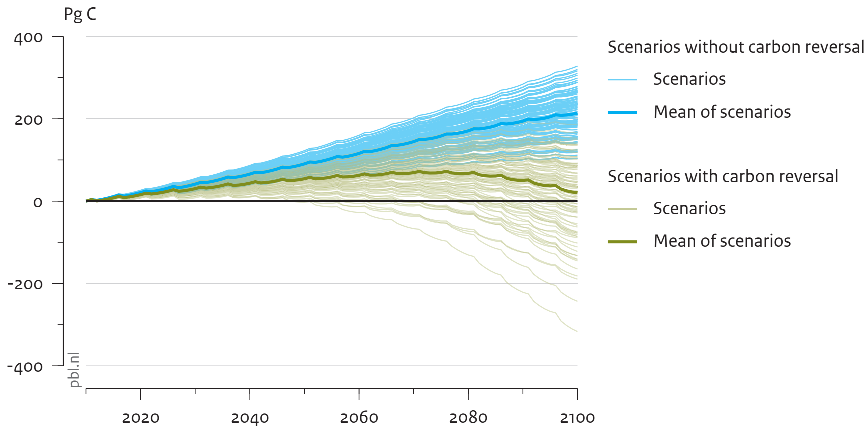


Source: PBL 2012

iterates with the agricultural production components as it provides input on potential productivity, while land used for agriculture and forestry is a key input. Changes in land cover, land use and climate at grid cell level have consequences for the carbon cycle, and for crop and grass productivity.

Example: Food consumption trends lead to net expansion of agricultural land, and thus to net loss of forest (mainly tropical forests). This results in net deforestation emissions as a result of human activities. After 2050, most IMAGE scenarios expect the net anthropogenic emissions from land-use change to decline further and to result in a small net uptake (as a result of demographic trends leading to a decline in land-use for food production). However, the terrestrial vegetation as a whole, which has been a large sink during the last decades, could become a CO_2 source as a result of climate change (Figure 2.7). This could lead to a rapid increase in atmospheric CO_2 concentration, given continued emissions from the energy system.

Figure 2.7
Cumulative terrestrial carbon flux of long-term climate scenarios



Source: Müller et al. in preparation

Cumulative terrestrial carbon flux using; positive numbers depict a cumulative terrestrial carbon sink, and negative numbers a cumulative terrestrial source (net carbon release exceeds the amount of carbon sequestered before). Although the terrestrial biosphere has always been a carbon sink, it may become a carbon source in the future (Müller et al., in prep.). See also Section 6.1.

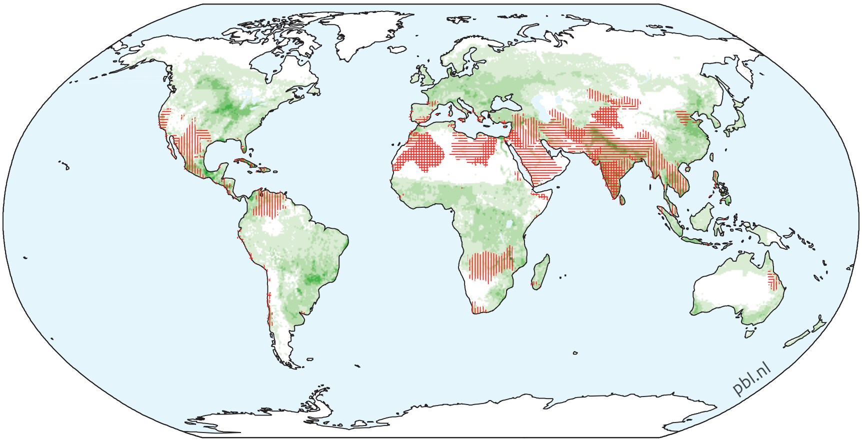
Water

The LPJmL model used for vegetation and carbon cycle also includes a global hydrology model (Section 6.3). With this linked hydrology model, IMAGE scenarios capture future changes in irrigated areas, water availability, agricultural water demand and water stress.

Water demand for irrigated agriculture is calculated in LPJmL, based on requirements for evapotranspiration for the crop types grown on irrigated land. For other sectors (households, manufacturing, electricity and livestock), water demand is calculated based on population, economic growth, industrial value added, and electricity production as projected with IMAGE-TIMER.

Example: Projected increases in agriculture, energy and industry production, and population lead to increased water demand. Climate change also impacts the water cycle. While overall climate change is projected to lead to more precipitation, geographical patterns show changes to drier and to wetter local climates. In addition, increasing temperature leads to more evapotranspiration. As a result, the water balance improves in some regions and deteriorates in other regions, and the pattern of these changes is very uncertain. In combination with increased demand, the areas confronted with crop production losses are projected to increase significantly as shown in Figure 2.8 for a similar scenario.

Figure 2.8
Regions vulnerable to crop production losses due to irrigation water shortage



Basins with irrigated crop production

Reduction more than 20% due to water shortage

More than 20% depending on groundwater

Crop production (t / grid cell)

Low High

Source: Biemans et al. 2012

Nutrients

The Nutrient model describes the fate of nitrogen (N) and phosphorus (P) emerging from concentrated point sources, such as human settlements, and from dispersed or non-point sources, such as agricultural and natural land (Section 6.4). The nutrient surplus eventually enters coastal water bodies via rivers and lakes. Key drivers that determine nutrient emissions include agricultural production with fertiliser application, and urban and rural populations, and their sanitation systems and level of wastewater treatment. For example, the model calculates the soil nitrogen balance from the total set of inputs and outputs. Inputs include biological nitrogen fixation, atmospheric nitrogen deposition, and application of synthetic nitrogen fertiliser and animal manure. Outputs include nitrogen removal from the field by crop harvesting, grass-cutting and grazing. The nutrient outflow from the soil combined with emissions from point sources and direct atmospheric deposition determine the loading of nutrients to surface water.

Example: In the Rio+20 scenario, further increase in the global population and growth of agricultural production add to pressures on the nutrient cycle. While increasing wastewater treatment and improved agricultural practices mitigate some of the increased nutrient loading, these processes are insufficient to offset increased fertiliser application to sustain intense agriculture. This leads to a significant further imbalance in nitrogen and phosphorus cycles, with consequences for water quality in rivers, lakes and coastal seas.

Atmospheric composition and climate change

Calculated emissions of greenhouse gases and air pollutants are used in IMAGE to derive changes in concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale (Section 6.5). Climatic change is calculated as global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model. Climatic change does not manifest uniformly over the globe. The patterns of temperature and precipitation are uncertain and differ between complex climate models. The changes in temperature and precipitation in each 0.5x0.5 degrees grid cell are derived from the global mean temperature using a pattern-scaling approach. The model accounts for feedback mechanisms related to changing climate, notably growth characteristics in the crop model, carbon dioxide concentrations (carbon fertilisation) and land cover (biome types).

Example: In the Rio+20 baseline, greenhouse gas emissions are projected to increase by about 60% in the 2010-2050 period. As a result, global temperature is expected to increase by around 4 °C above pre-industrial levels by 2100 without climate policy, and most likely exceeding 2 °C before 2050 (Figure 2.6). Rapid emission reductions, however, could limit temperature increase, most likely, to less than 2 °C.

7. Impacts of environmental change

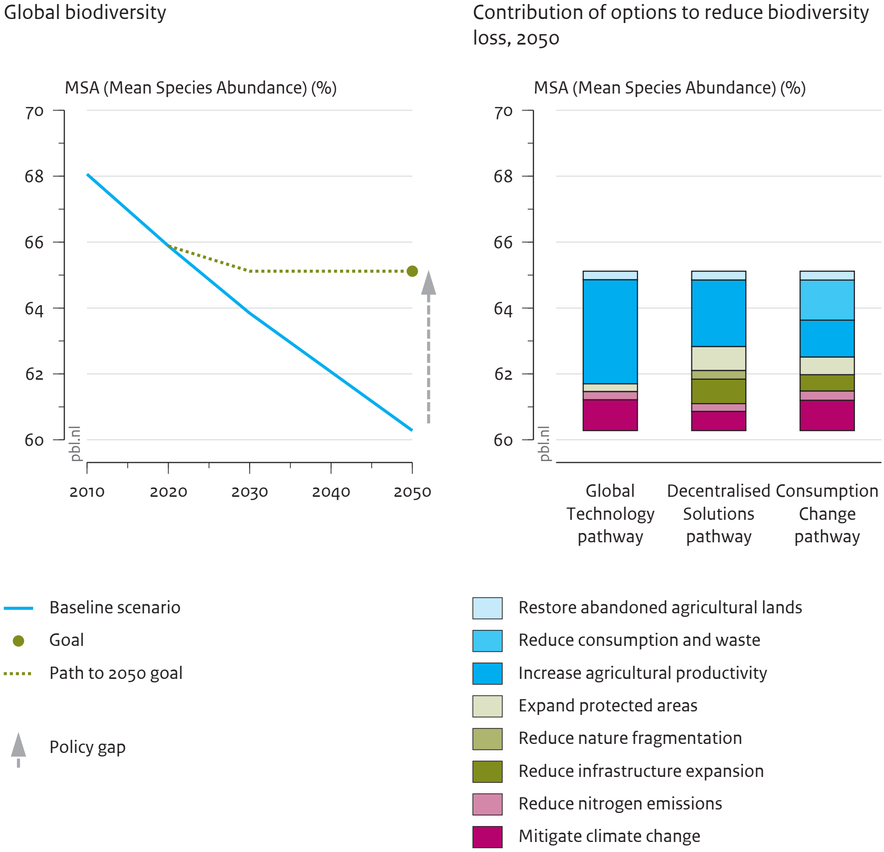
Several impacts of global environmental change are calculated in IMAGE (Chapter 7). Here we briefly describe biodiversity loss and impacts on human development.

Biodiversity loss

Biodiversity loss is assessed by the impact model GLOBIO (Section 7.2) as calculated changes in mean species abundance (MSA). The MSA indicator maps the effect of direct and indirect drivers of biodiversity loss provided by IMAGE, including climate, land-use change, ecosystem fragmentation, expansion of infrastructure, disturbance of habitats, and acid and reactive nitrogen deposition. Their compound effect on biodiversity is computed with the GLOBIO3 model for terrestrial ecosystems. As IMAGE and GLOBIO3 models are spatially explicit, the impacts on MSA can be analysed on a grid by region, main biome and pressure factor. A similar model has been developed to map biodiversity in fresh water (Section 7.3).

Example: A further decline in biodiversity is projected in the Rio+20 baseline at an almost historical rate (Figure 2.9). While historically habitat loss has been the key driver of biodiversity loss, more important pressures in the coming decades are projected to be climate change, forestry and infrastructure.

Figure 2.9
Global biodiversity under baseline and sustainability scenarios to prevent biodiversity loss



Source: PBL 2012

Biodiversity is projected to decline further in the baseline scenario (left). Various measures contribute to reducing biodiversity loss in the sustainability scenarios (right).

Human development

Changes in the global environmental impact on human development in many ways. Via the link to the GISMO model, the IMAGE framework describes impacts on human health, and the achievement of human development goals such as the Millennium Development Goals (MDGs; see Section 7.7). The health module describes the burden of disease per gender and age, including communicable diseases, and also health impacts of air pollution and undernourishment, and interactions between these factors.

The model puts the impacts of global environmental change in perspective of other factors determining human health. For instance, hunger is defined as the proportion of the population with food consumption below the minimum dietary energy requirement. The model determines hunger on the basis of distribution of food intake over individuals calculated on the mean food availability per capita (from other parts of IMAGE), and a coefficient of variation.

Water supply levels and sanitation are modelled separately for urban and rural populations by applying an empirical regression model, depending on per capita GDP, urbanisation rate and population density.

Example: With regard to global hunger, the Rio+20 scenario shows improvement compared to the last few decades. This improvement is a consequence of rapid income growth in low-income regions and levelling off of population growth (Figure 2.10).

Other impacts

Other impacts calculated in the IMAGE framework using separate impact models include flood risks (Section 7.4), land degradation (Section 7.5) and ecosystem services (Section 7.6). Many impacts of global environmental change are an integral part of the components in the Human system and the Earth system, such as water stress and climate change impact on crop yields (Section 7.1).

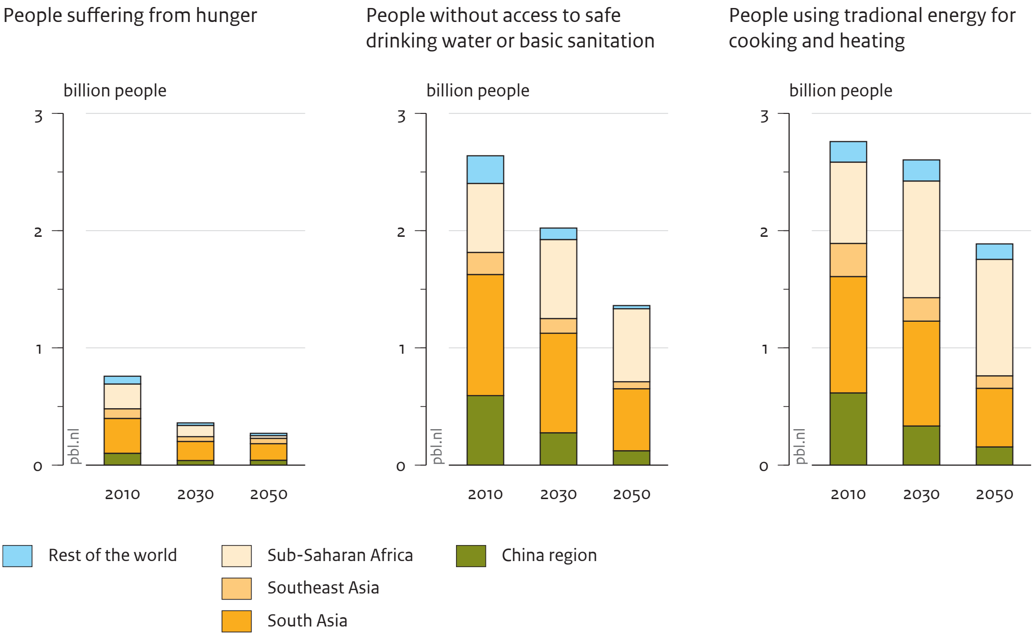
2.3 Policy issues

The IMAGE framework can be used to explore policy issues in a variety of areas. These include possible impacts in the absence of new policies or policy responses, and evaluation of possible policy interventions. IMAGE provides an integrated perspective on policy issues by assessing options in various part of the Human and the Earth system and evaluating the impact from several perspectives.

The model assesses the following key areas for policy responses:
- Climate policy (global targets, regional efforts, costs and benefits)
- Energy policies (air pollution, energy access, energy security and bioenergy)
- Land and biodiversity policies (food, bioenergy, nature conservation)
- Human development policies (malnutrition, health)
- Measures to reduce the imbalance of nutrient and water cycles.

The first three are discussed below.

Figure 2.10
Human development indicators under the baseline scenario



Source: PBL 2012

The baseline scenario also shows a decline in population without access to safe drinking water, sanitation and modern energy. In all cases, the improvement is too slow compared to policy ambitions

Climate policy

A key focus of the IMAGE framework is climate change mitigation strategies. For this purpose, IMAGE is linked to the FAIR model (Section 8.1) to assess detailed climate policy configurations in support of negotiation processes, and also for inter-temporal optimisation of mitigation strategies. FAIR receives information from various parts of IMAGE, including baseline emissions from energy, industry and land use, the potential for reforestation, and the costs to emission abatement in the energy system. The latter is provided in dynamic marginal abatement cost (MAC) curves, based on the IMAGE energy model, by regions, gases and sources. Using demand and supply curves, the model determines the carbon price on the international trade market, and the resulting net abatement costs for each region.

Long-term reduction strategies can be determined by minimising cumulative discounted mitigation costs. The FAIR results are fed back to the core IMAGE model to calculate impacts on the energy and land-use systems. Together, FAIR and IMAGE can be used to assess the relative importance of mitigation measures and the potential impacts of climate policy, such as avoided damage and co-benefits for air pollution.

Energy policies

The IMAGE framework can be used to assess a wider range of energy policies than climate policy alone, including measures to promote access to modern energy and to improve energy security (Section 8.2). Moreover, it is possible to constrain or even ban the use of specific technologies, such as bioenergy, nuclear power and carbon capture storage. IMAGE analysis incorporates linkages, synergies and trade-offs in global change processes, such as the link between energy use and land use for bioenergy, and the consequences of air pollution for human health.

Land and biodiversity policies

Policies on land use and biodiversity can be introduced in the various IMAGE components (for an overview, see Section 8.3). These include changes in the agro-economic model (trade policies, subsidies, taxes, yield improvements, and dietary preferences) and the land-use system (restriction on certain land-use types, REDD). As a linked system, IMAGE can assess the system-wide consequences of measures introduced, including trade-offs and feedbacks, such as the consequences of agricultural policies for nutrient cycles, biodiversity and hunger. Key examples are evaluation of dietary changes with respect to biodiversity, land-use and greenhouse gas emissions, and evaluation of more stringent land-use planning and REDD on biodiversity conservation and food security.

2.4 Data, uncertainties and limitations

Data

Many IMAGE components rely on a number of key data sources. The main data sources are listed in Table 2.1 and described in Chapters 3 to 7 for the respective IMAGE components.

Uncertainties

Systematic uncertainty analyses have been performed on the individual IMAGE models. In addition, IMAGE has been assessed in model comparison projects (e.g., AgMIP via MAGNET; Von Lampe et al. (2014)). These studies also contribute to understanding key uncertainties, as the experiments in these projects tend to be set up in the form of sensitivity runs, in which comparison with other models provides useful insights. An overview of key uncertainties in the IMAGE framework is presented in Table 2.2.

Table 2.1: Main data sources for the IMAGE model

Categories	Main data sources
Energy	International Energy Agency (IEA, 2012a); fossil fuel resources (USGS, 2000; Mulders et al., 2006); renewable energy resources (Hoogwijk, 2004); various sources on technology assumption (see Chapter 3).
Land use and agricultural production/consumption	Data on national crop and livestock production, agricultural yields, and land resources from FAO (2013a)
Emissions	EDGAR database (JRC/PBL, 2012)
Climate data	Historic climate data (CRU global climate dataset; AR4 data repository (IPCC-DDC, 2007)
Costs data climate policy (other than energy)	Lucas et al. (2007)

Table 2.2: Overview of key uncertainties in the IMAGE framework.

Model component	Uncertainty
Drivers	Overall population size, economic growth
Agricultural systems	Yield improvements, meat consumption, total consumption rates
Energy systems	Preferences, energy policies, technology development, resources
Emissions	Emission factors, in particular those in energy system
Land cover / carbon cycle	Intensification versus expansion, effect of climate change on soil respiration, CO_2 fertilization effect
N-cycle	Nutrient use efficiencies
Water cycle	Groundwater use, patterns of climate change
Climate system	Climate sensitivity, patterns of climate change
Biodiversity	Biodiversity effect values, effect of infrastructure and fragmentation

Limitations

The IMAGE model is relatively strong in the representation of the physical world in the Earth system, and the resource and technology selection in the Human system. A high level of integration has been achieved of these systems, with key parameters exchanged across many parts of the model (e.g. bioenergy, temperature feedbacks on crop production and the energy system, consistent treatment of climate policy and a consistent model for land cover and the carbon and water cycle).

However, there are also several limitations to the model:

- The economy is represented separately in different model components, notably in the agriculture and energy models with monetary feedback not well represented in the energy model. This implies that the model is better adapted for long-term trends than for short-term issues, and is not suitable to assess detailed economic impacts, such as sector level impacts.
- A model run starts in 1970, which implies that 2010 is model output. The model is calibrated against historical data up to 2005 and to 2010, depending on the module, which has implications for applications that use IMAGE output for the 2010-2020 period (for instance, evaluation of 2020 policies by FAIR).
- By design, the model is aggregated to allow for global coverage and a long time horizon, while keeping run times in check. Detailed, differentiated processes at local scale and national policies are represented as part of global region trends, without taking into account country-specific measures and processes.
- The physical orientation implies that the model is well adapted to study technical measures to achieve policy goals, but less so to study specific policies. Some policies, such as a carbon tax, can be represented but others, such as R&D policies, cannot. The model has no representation of governance systems, which tend to be handled as exogenous (variant) scenario parameters serving as proxies.

DRIVERS

DRIVERS

3

3 Drivers

Tom Kram, Detlef van Vuuren, Elke Stehfest

1. Introduction

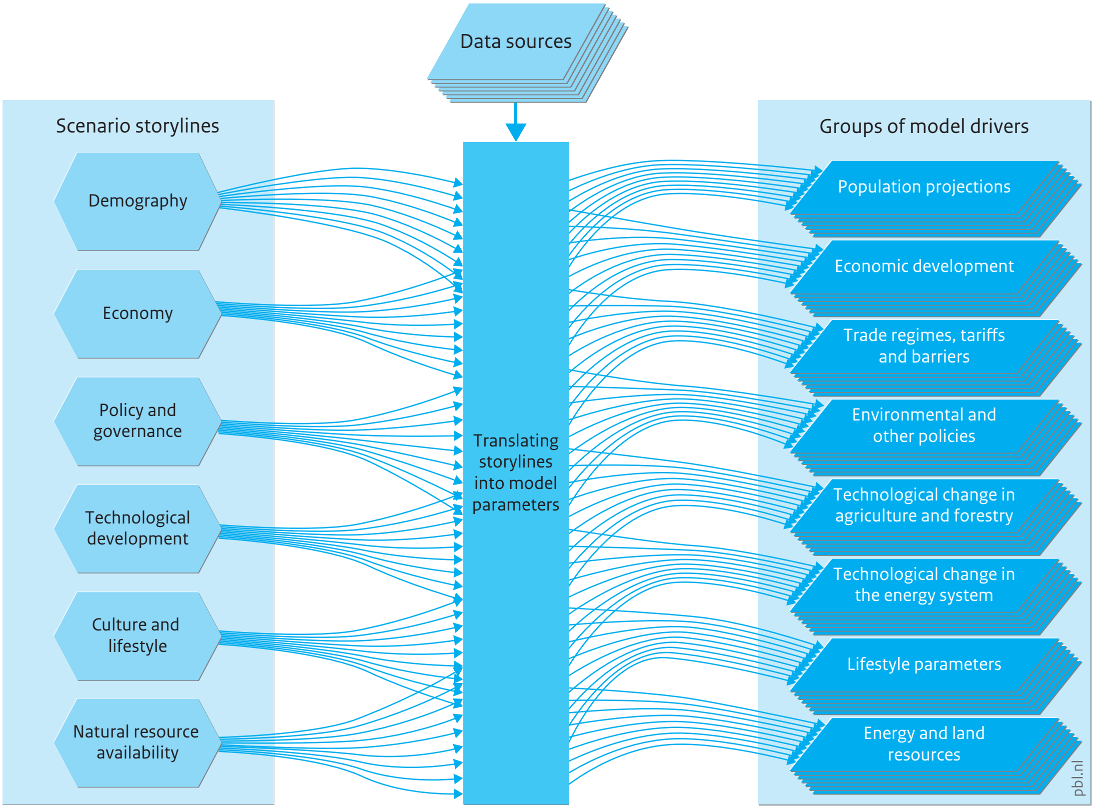
To explore future scenarios, exogenous assumptions need to be made for a range of factors that shape the direction and rate of change in key model variables and results. Together with the endogenous functional relationships and model parameters that typify model behaviour, these exogenous assumptions drive the outcome of model calculations. These assumptions are the **drivers** that determine the model results, subject to the assumed external conditions.

In IMAGE, six groups of assumptions are distinguished that make up the **scenario drivers.** These six groups are the basis for all scenarios and are embedded in a scenario narrative or storyline. This includes cases where current trends and dynamics are assumed to continue into the future, commonly referred to as reference or 'business-as-usual' scenarios. But scenario drivers can also be used to describe a set of contrasting future futures to explore the relevant range of uncertain yet plausible developments.

As a rule, scenario drivers are not numerical model inputs but, in qualitative or semi-quantitative terms, govern a detailed set of exogenous assumptions in terms of model input to the various components of the model framework. Numerical model drivers for a specific scenario are established on the basis of the six generic scenario drivers. The model drivers for the various IMAGE models and modules are explained in Chapters 4 to 8.

The scenario drivers and underlying narrative, together with the quantitative model drivers, form a scenario that is inextricably linked with the results from an IMAGE scenario run.

Figure 3.1
Scenario development and model drivers for IMAGE 3.0



Source: PBL 2014

Model drives are inferred from scenario storylines taking into account external data sources, such as time series, cross-sector data, and literature sources. More detail on model drivers and their use in other IMAGE components is presented in Table 3.1

3

2. Model description

Scenario drivers

On the basis of how the world may develop in the longer term, the following six key scenario drivers are distinguished: demography, economy, culture and lifestyle, natural resource availability, technological development, and policy and governance (Figure 3.1). The future direction of these drivers is often inferred from the storyline or narrative, which may range from brief to very detailed. The storyline describes the following scenario types and functions:

- reference projection with no new policies (OECD, 2008);
- single 'best guess' projection combining past trends with assumptions on how they may develop (PBL, 2010; PBL, 2011);
- multiple contrasting scenarios that span a range of uncertainties about the future (IPCC, 2000; MA, 2005; Moss et al., 2010; IIASA, 2013);
- specific or broad policy scenarios directed to improving future outcomes (OECD, 2012; PBL, 2012).

Demography

The future state of the world depends on the population because total demand for goods and services equals the number of people times demand per capita.

Most population projections used as input to the IMAGE model have been adopted from published sources, such as data from the United Nations (UN, 2013) and projections by the International Institute for Applied Systems Analysis (IIASA) (Lutz and KC, 2010). Behind these numerical projections are economic, technical, educational and policy assumptions that determine the estimated future population as the net outcome of fertility and mortality, adjusted for migration flows. This has provided internally consistent, overall population scenarios on the basis of underlying demographic trends.

In addition to total number of people, the population is broken down into gender, income classes, urban and rural, and educational level. These attributes are relevant for issues such as consumption preferences and patterns, and access to goods and services. Using a downscaling procedure (Van Vuuren et al., 2007b), national and regional population can be projected at grid level to account for trends in urbanisation and migration within countries and regions.

Population data are used in energy and agricultural economics modelling, and in other IMAGE components, such as water stress, nutrients, flood risks and human health.

Economy

At the most aggregated level, economic activity is described in terms of gross domestic product (GDP) per capita. Models outside the IMAGE 3.0 framework, such as the OECD ENV-Growth model, project long-term GDP growth based on developments in key production factors (e.g., capital, labour, natural resources), and the sector composition of the economy. The various components of GDP on the production side (in particular value added (VA) per sector) and expenditures (in particular private consumption) are estimated with more detailed models that take account of inter-sector linkages, own- and cross-price responses, and other factors (Chateau et al., 2013).

In IMAGE 3.0, economic variables are used as model drivers for the energy demand model (Section 4.1.1), and non-agricultural water demand contributing to water stress (Section 6.3). To meet the requirements of the household energy demand model, average income is broken down into urban and rural population, and each population into quintiles of income levels. The latter is derived from the assumed uneven income distribution using the GINI factor, a measure of income disparity in a population. The macro indicator GDP per capita is also used directly in IMAGE components, such as human health, flood risk, and nutrients (for calculating urban wastewater). The agriculture model MAGNET is an economy-wide computable general equilibrium (CGE) model that reproduces exogenous GDP growth projections made in less complex economic growth models, see Section 4.2.1.

Policy and governance

Scenarios may differ considerably with regard to assumptions on implicit or explicit policies that reflect alternative future developments in human and natural systems, and assumptions on the evolution of governance structures and institutional settings. While policy thinking may vary, a key scenario split in IMAGE is more focus on the shorter term and/or on material wealth, or focus on longer term sustainability concerns. Based on this, inter-regional and/or inter-generational equity may be awarded more or less weight as an underlying future trend. As mentioned under culture and lifestyle, such assumed directions in overall policy have the potential to influence almost all relevant scenarios and model drivers.

In addition to alternative policy directions, other important factors are developments in governance structures and institutions in different world regions, or in groups of regions sharing certain characteristics. For instance, this may concern high-income industrialised countries, medium income emerging economies, or low-income developing countries.

Other elements may also make some policy measures and instruments more or less plausible. For example, a concerted and jointly implemented global climate mitigation strategy is less conceivable in a world with diverging regions primarily pre-occupied with short-term domestic interests and weak intergovernmental bodies.

Technological development

At scenario level, the assumed technical progress is the key driver of economic growth. Given an effective labour force, the increase in labour productivity delineates the potential for economic growth. In scenarios, it is generally assumed that the degree of technical progress is reflected in all areas where technology plays a role. Thus, an assumed rapid growth in technology leading to high economic growth implies that technological options in specific sectors (e.g., energy and agriculture) will also develop relatively quickly. However, the directions of technological change may differ within and across sectors. For example, renewable energy technologies may improve more rapidly than fossil fuel based technology. Thus, this is an uncertain factor.

Box 3.1 Example of a model driver: technological change in agriculture

The management factor (MF) describes the actual yield per crop group and per socio-economic region as a proportion of the maximum potential yield. This maximum potential yield is estimated taking into account inhomogeneous soil and climate data across grid cells. The MF for the period up to 2005 is estimated as part of the IMAGE calibration procedure, using FAO statistics on actual crop yields and crop areas (FAO, 2013a). The start year for the MF is subsequently taken as point of departure for future projections.

Guidance for future development of yield changes is provided by expert projection such as the assumptions in FAO projections up to 2030 and 2050 (Bruinsma, 2003; Alexandratos and Bruinsma, 2012).The FAO trends are used as exogenous technical development in the MAGNET model, and subsequently adjusted to reflect the relative shortage of suitable land, as part of the model calculation (Section 4.2.1). The combinations of production volumes and land areas from MAGNET are adopted as future MF projections into the future in IMAGE.

Future technological change is dependent on the storyline and needs to be consistent with other scenario drivers. For instance, strong economic growth is typically facilitated by rapid technology development and deployment, rising wages and a labour shift from primary production (agriculture) to secondary (industry) and tertiary (services) sectors. These developments foster more advanced management and technology in agriculture. In order to reflect different trends in exogenous yield increase, FAO trends are combined with projections of economic growth to develop scenario-specific trends of yield changes in multiple-baseline studies, like for the SSPs. Because the MF is such a decisive factor in future net agricultural land area, careful consideration of uncertainties is warranted.

In the energy sector (see Section 4.1), technology improvements over time are largely governed by an endogenous mechanism that links technology cost to the cumulative capacity, learning by doing. Technological factors in agriculture are estimated exogenously, based on historical data and projections from the literature on crop and livestock productivity, efficiency in water and fertiliser use, and performance of irrigation systems.

Culture and lifestyle
For comparable levels of affluence, observed consumption behaviour differs greatly between countries and regions, and to a lesser extent within countries. The modal split for passenger transport by walking, bicycle, car, bus, train, boat and aircraft depends on income, but also on engrained traditions and habits of social groups. Food preferences depend on availability and affordability, and also greatly on cultural factors, such as religion (e.g., no pork for Jewish and Islamic households, and no beef or no meat at all for Hindus), and on tradition, values and health concerns. In addition, behaviour may be influenced by concerns about environmental degradation, animal welfare, inter-regional and inter-generational equity, and other issues according to dominant social norms and values.

Consumer preferences and lifestyles may change over time, as may norms and values. The direction and rates of change can be inferred from the underlying scenario storyline. Policies may be put in place to enable, encourage or even induce change, given sufficient public support.

Natural resource availability
The term, ultimate natural resources, refers to the amount of resources theoretically available if not affected by human activity. For non-renewable resources, such as coal and iron ore, this concerns the accumulated amount before human extraction began. For renewable resources, such as solar energy, it represents the solar radiation intercepted on Earth in a given time period. As the ultimate quantities of these natural resources cannot be changed by humans, they cannot be considered as scenario drivers in IMAGE. Similarly, the global land area is fixed, except for relatively limited reclaimed areas in shallow coastal waters and natural processes by which land area is increased (e.g., volcanic islands) and land area is reduced (e.g., coastal erosion).

The quantity of a resource available in the future depends on exogenous assumptions for the scenarios. The estimated quantities depend on the assumed future technology capabilities, policies and human preferences. Higher estimates of non-conventional fossil fuels and nuclear fuel reserves are associated with technology optimism, for example, estimates of natural gas reserves depend on whether the extraction of deep seabed methane is considered a viable option. Nature conservation and other issues may limit the potential for natural land conversion for agriculture, but may also impose limits on hydroelectricity generation.

In IMAGE 3.0, renewable and non-renewable energy resources are modelled by volume and price, see Section 4.1.3. Similarly, the potential land for agriculture, ranked according to suitability is subject to nature conservation policies, which limits future land conversion, see Section 4.2.3.

Relationships between scenario drivers

Assumptions made in one of the six scenario drivers depend, to a lesser or greater extent, on assumptions in one or more of the other scenario drivers. Thus, the plausibility of a set of drivers and of an individual driver hinges on careful consideration of the nature and direction of these relationships. An overarching story or narrative has proven helpful in selecting meaningful combinations of scenario drivers (IPCC, 2000; MA, 2005).

Model drivers

Direct model drivers are inferred from the scenario drivers and used in setting the parameter values in IMAGE 3.0. The start values are estimated from the literature and data, and future changes in values are inferred from the narratives and scenario drivers (Figure 3.1). The resulting parameter values are used as input for different parts of IMAGE 3.0. A list of most important model drivers, their source and their use in IMAGE components (Chapter 4-8) is given in Table 3.1.

Table 3.1
Model drivers

	Driver	Description	Source	Use (section)
Population	Population	Number of people per region.	UN; future: exogenous input	4.1.1, 4.2.1, 8.1
	Population - grid	Number of people per gridcell (using downscaling).	UN; own downscaling	4.2.3, 6.4, 7.4,7.7
	Urban population fraction	Urban/rural split of population.	UN; future: exogenous input	7.7
Economy	Private consumption	Private consumption reflects expenditure on private household consumption. It is used in IMAGE as a driver of energy.	The World Bank; future: exogenous input	4.1.1
	Capital supply	Capital available to replace depreciated stock and expand the stock to support economic growth.	GTAP database	4.2.1
	Labour supply	Effective supply of labour input to support economic activities, taking into account the participation rate of age cohorts.	Demographics: population by age cohort times participation rate, corrected for skill level	4.2.1
	GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	Own downscaling	6.4, 7.4, 7.6
	GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	World Bank database; future: exogenous input	4.1.1, 4.2.1, 5.2, 7.7, 8.1
	GINI coefficient	Measure of income disparity in a population. If all have the same income, GINI equals 1. The lower the GINI, the wider the gap between the lowest and highest income groups.	World Bank database; future: scenario assumptions	7.7
	Sector value added	Value Added for economic sectors: Industry (IVA), Services (SVA) and Agriculture (AVA). These variables are used in IMAGE to indicate economic activity.	Various sources	4.1.1
	Timber demand	Demand for roundwood and pulpwood per region.	FAO; future: exogenous input or own calculation	4.2.2
Trade	Trade restriction	Trade tariffs and barriers limiting trade in energy carriers (in energy submodel).	Own assumptions	4.1.3
	Agricultural trade policy	Assumed changes in market and non-market instruments that influence trade flows.	Literature and own assumptions	4.2.1

	Driver	Description	Source	Use (section)
Policies	Energy policy	Policy to achieve energy system objectives, such as energy security and energy access.	Own assumptions	4.1.2
	Taxes and other additional costs	Taxes on energy use, and other additional costs	IEA; future: scenario assumptions	4.1.1
	Air pollution policy	Air pollution policies set to reach emission reduction targets, represented in the model in the form of energy carrier and sector specific emission factors.	EDGAR database; future based on own assumptions	4.1.2
	Biofuel policy	Policies to foster the use of biofuels in transport, such as financial incentives and biofuel mandates and obligations.	Literature and own assumptions	4.2.1
	Protected area - grid	Map of protected nature areas, limiting use of this area.	WDPA database; own assumptions, derived from polygon maps	4.2.3, 5.1, 7.2, 7.6
	Climate target	Climate target, defined in terms of concentration levels, radiative forcing, temperature targets, or cumulative emissions.	Own assumptions	8.1
	Domestic climate policy	Planned and/or implemented national climate and energy policies, such as taxes, feed-in tariffs, renewable targets, efficiency standards, that affect projected emission reduction.	Own assumptions	8.1
	Equity principles	General concepts of distributive justice or fairness used in effort sharing approaches. Three key equity principles are: Responsibility (historical contribution to warming); capability (ability to pay for mitigation); and equality (equal emissions allowances per capita).	Expert judgement	8.1
	Adaptation level	Level of adaptation to climate change , defined as the share of climate change damage avoided by adaptation. This level is be calculated by the model to minimise adaptation costs and residual damage, or set by the user.	Own assumptions, optimisation	8.1
Technology agriculture	Technological change (crops and livestock)	Increase in productivity in crop and grass production (yield/ha) and livestock production (carcass weight, offtake rate, feed).	FAO; own estimates	4.2.1
	Production system mix	Livestock production is distributed over two systems (intensive: mixed and industrial; extensive: pastoral grazing), with specific intensities, rations and feed conversion ratios.	Own estimates; Bouwman et al. (2005)	4.2.4, 6.4

	Driver	Description	Source	Use (section)
Technology agriculture (continued)	Livestock rations	Determines the feed requirements per feed type (feed crops; crop residues; grass and fodder; animal products; foraging), specified per animal type and production system (extensive/intensive).	Own estimates; Bouwman et al. (2005)	4.2.4, 6.4
	Animal productivity	Effective production of livestock commodities per animal per year.	FAOSTAT database; future: scenario assumptions	4.2.4
	Feed conversion	Measure of an animal's efficiency in converting feed mass into the desired output such as meat and milk (for cattle, poultry, pigs, sheep and goats).	FAOSTAT database; future: scenario assumptions	4.2.4
	Irrigation project efficiency	Ratio of quantity of irrigation water required by the crop (based on soil moisture deficits) to the quantity withdrawn from rivers, lakes, reservoirs or other sources. This parameter is given at country level.	PIK ; Rohwer et al. (2007)	6.3
	Irrigation conveyance efficiency	Ratio of water supplied to the irrigated field to the quantity withdrawn from the water source, determining the quantity of water lost during transport. This parameter is defined at country level.	PIK ; Rohwer et al. (2007)	6.3
	Increase in irrigated area - grid	Increase in irrigated area, often based on external projections (e.g., FAO).	IIASA and FAO (2012); Own assumptions for spatial allocation	4.2.3
	Fertiliser use efficiency	Ratio of fertiliser uptake by a crop to fertiliser applied.	FAOSTAT database; future: scenario assumptions Bouwman et al. (2013c)	6.4
	Manure spreading fraction	Fraction of manure produced in staples that is spread on agricultural areas.	Own estimates; Bouwman et al. (2013c)	6.4
	Forest plantation demand	Demand for forest plantation area.	FAOSTAT database; future: scenario assumptions	4.2.2
	Fraction of selective logging	The fraction of forest harvested in a grid, in clear cutting, selective cutting, wood plantations and additional deforestation. Fraction of selective cut determines the fraction of timber harvested by selective cutting of trees in semi-natural and natural forest.	Own estimates, based on FAO	4.2.2
	Harvest efficiency	Fraction of harvested wood used as product, the remainder being left as residues. Specified per biomass pool and forestry management type.	Various sources	4.2.2

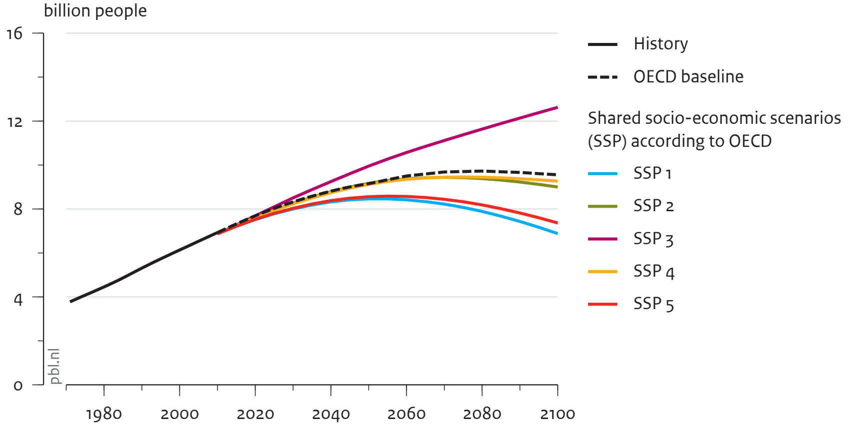
	Driver	Description	Source	Use (section)
Technology energy	Energy intensity parameters	Set of parameters determining the energy use per unit of economic activity (in absence of technical energy efficiency improvements).	IEA; future: own calculations and scenario assumptions	4.1.1
	Energy efficiency technology	Model assumptions determining future development of energy efficiency.	Own assumptions	4.1.1
	Technology development of energy supply	Learning curves and exogenous learning that determine technology development.	Scenario assumptions based on various sources	4.1.3
	Learning rate	Determines the rate of technology development in learning equations.	Literature and scenario assumptions	4.1.3
	Technology development of energy conversion	Learning curves and exogenous learning that determine technology development.	Scenario assumption based on various sources	4.1.2
Lifestyle	Lifestyle parameters	Lifestyle parameters influence the relationship between economic activities and demand for energy.	IEA; based on calibration	4.1.1
	Preferences	Non-price factors determining market shares, such as preferences, environmental policies, infrastructure and strategic considerations, used for model calibration.	Calibration,future: scenario assumptions	4.1.1
Resources	Energy resources	Volume of energy resource per carrier, region and supply cost class (determines depletion dynamics).	Rogner (1997); Mulders et al. (2006)	4.1.3
	Built-up area	Urban built-up area per grid cell, excluded from all biophysical modelling and increasing over time as a function of urban population and a country- and scenario-specific urban density curve.	Klein Goldewijk et al. (2010)	5.1

3. Policy issues

Baseline developments

Under baseline conditions, scenario drivers are assumed to develop either along the pathway considered the 'best guess' translation of current trends into the future, or multiple contrasting scenarios are considered to explore the range of plausible future trends. The first approach has been chosen for many studies, such as the OECD Environmental Outlook to 2050 (OECD, 2012), as starting point for policy interventions to improve the baseline outcomes within and across sectors and issues. The second approach recognises structural uncertainties in how the world may develop, and explores how such uncertainties would play out in a future range of outcomes. Multiple contrasting scenarios also serve to investigate how robust policy interventions play out under different future conditions. Examples of multiple baseline studies are the Special Report on Emissions Scenarios (IPCC, 2000) and the Millennium Ecosystem Assessment (MA, 2005).

Figure 3.2
Population under the OECD baseline and SSP scenarios



Source: OECD 2012; IIASA 2013

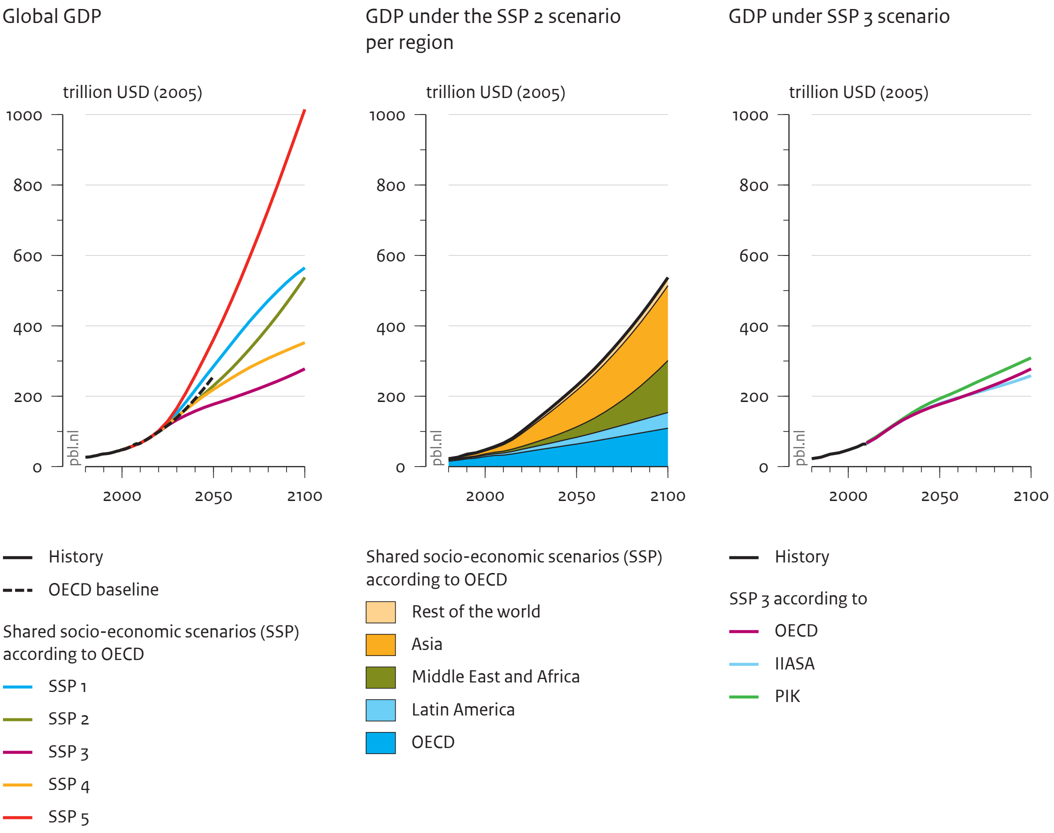
Total global population is projected to peak and then decline in the coming century, except under the high-end assumptions (SSP3). By 2100, the population may range between the current level and twice as many than in 2000 in the SSPs. The OECD Outlook assumes an intermediate population growth trajectory, close to the medium population SSP scenarios.

Recently, the *Shared Socioeconomic Pathways* (SSPs) have been developed to support climate change research by different research communities (Moss et al., 2010; Van Vuuren et al., 2012; Ebi et al., 2013). See Figures 3.2 and 3.3. The qualitative narratives or storylines characterising alternative futures are important elements of the SSPs From there, assumptions are made about internally coherent sets of scenario drivers, and key model drivers, such as population and GDP growth (IIASA, 2013)

The wide range of long-term populations projections is presented in Figure 3.2. By 2100, the world population could be either about the same as today or double. The projections were made by IIASA using a population modelling approach (Lutz and KC, 2010) that links aggregate education levels to fertility and mortality rates per country. Together with migration flows, these rates determine the size of the future population. (Dellink et al., forthcoming; KC and Lutz, forthcoming).

Using population projections and the underlying educational attainment per age cohort, long-term economic growth models project economic development expressed as GDP per capita. For the SSPs, economic development up to 2100 has been calculated by three different teams at OECD, IIASA and PIK, using their own models. GDP projections from the OECD model ENV-Growth (Dellink et al., forthcoming) differ by a factor of up to 3.7 (see Figure 3.3, left). The differences in population and economic growth rates between

Figure 3.3
GDP under OECD baseline and the SSP scenarios



Source: OECD 2012; IIASA 2013

Projected total world GDP in the OECD environmental outlook (OECD, 2012) and in the SSP scenarios according to OECD (left), per world region in SSP2 according to OECD (middle) and according to different sources for SSP3 (right). GDP (Gross Domestic Product) is shown in purchasing power parity (ppp), SSP data from SSP database (IIASA, 2013).

countries and regions mean that the distribution of total economic assets is likely to shift, with Asia in the lead, followed later by Africa and, to a lesser extent, by Latin America (see Figure 3.3, middle).

As different models have been used, we can investigate how different model structures and assumptions and different interpretations of the qualitative scenario storylines in model parameters lead to quite different results (Figure 3.3, right). Projections for the SSP3 scenario made by different teams not only differ with respect to the levels projected for 2100, but also with respect to the profile over the century.

For more information on baseline scenarios in economic, social and ecological terms, see the results obtained in the IMAGE 3.0 framework in Chapters 4 to 8.

Policy interventions

Once baseline scenarios are implemented, modifications can be made at various levels to reflect policy interventions diverging from the trends emerging under baseline conditions. These modifications can vary depending on the subject, scale, timeframe and policy levers under consideration, for instance, reducing climate change impacts, reducing the nutrient loading of coastal waters, slowing down the rate of biodiversity loss, and reducing water stress. These and many other options to alleviate anticipated future problems have been explored with IMAGE. More information on policies, instruments and goals is provided in Chapters 4 to 8.

4. Key publications

IPCC (2000). Special report on emissions scenarios, N. Nakicenovic and R. Swart (eds.). Cambridge University Press, Cambridge (UK) / New York.

OECD (2012). OECD Environmental outlook to 2050: The consequences of inaction OECD Publishing, Paris.

MA (2005). Ecosystems and human well-being: Scenarios, S.R. Carpenter, P. Pingali, E.M. Bennet and M.B. Zurek (eds.), *Millennium Ecosystem Assessment*. Island Press Washington, D.C.

HUMAN SYSTEM

HUMAN SYSTEM

4 Human system

4.1 Energy Supply and Demand

Key policy issues

- How can energy supply and demand become more sustainable, balancing human development, security of supply, and concerns about climate change and air pollution?
- What transitions in the energy system would meet long-term climate goals?
- How are these strategies affected by uncertainties in the energy system?

1. Introduction

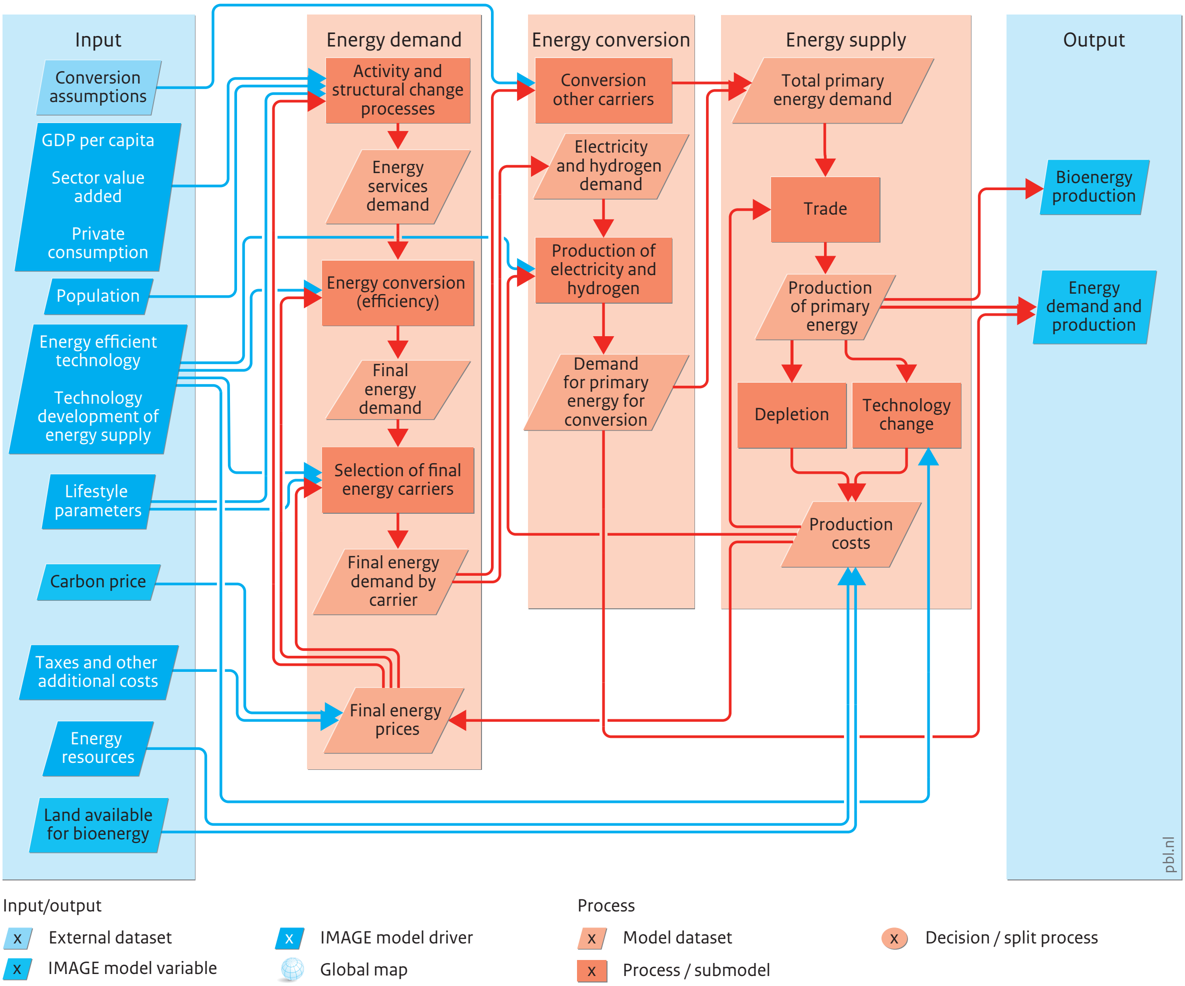
Energy consumption and production constitutes a central component in discussions on sustainable development. Without the use of energy most human activities are impossible. Hence, securing a reliable and affordable supply of fit-for-purpose energy is an important element of countries' economic and energy policies. Three-quarters of the world's energy supply is fossil fuel. However, over time, depletion of fossil fuel resources is expected to lead to rising prices at least for oil, and easily accessible resources will be concentrated in a decreasing number of countries. Energy consumption and production is also important for environmental reasons as fuel combustion is the single most important source of local and regional air pollution and greenhouse gas emissions.

The future of the global energy system is highly uncertain and depends on factors such as technological innovations and breakthroughs, socio-economic developments, resource availability and societal choices. Exploring different scenarios for developments around the use and supply of energy provides information for decision-makers to base strategic policy decisions.

The IMage Energy Regional model, also referred to as TIMER, has been developed to explore scenarios for the energy system in the broader context of the IMAGE global environmental assessment framework (De Vries et al., 2001; Van Vuuren, 2007). TIMER describes 12 primary energy carriers in 26 world regions and is used to analyse long-term trends in energy demand and supply in the context of the sustainable development challenges.[1] The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the

1 The words energy demand and energy use are often used interchangeably. However, in the past data were about statistical energy *use*. For the future, trends were extrapolated and denoted as energy *demand*, which in the model is assumed to be fully supplied and thus equal to use.

Figure 4.1.1
TIMER, the energy demand and supply model in IMAGE 3.0



Source: PBL 2014

energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

Similar to other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. In this respect, TIMER differs from most macro-economic models, which let the system evolve on the basis of minimising cost or maximising utility under boundary conditions. As such, TIMER can be compared to energy simulation models, such as POLES (Criqui et al., 2003) and GCAM (Thomson et al., 2011).

2. Overview of TIMER

The energy model has three components: energy demand; energy conversion; and energy supply (Figure 4.1.1). The energy demand component describes how energy demand is determined for five economic sectors -industry, transport, residential, services and other sectors. The energy conversion components describes how carriers such as electricity and hydrogen are produced. Finally, the energy supply modules describe the production of primary energy carriers, and calculate prices endogenously for both primary and secondary energy carriers that drive investment in the technologies associated with these carriers. The energy flows in all three main components allow calculation of greenhouse gas and air pollutant emissions.

The energy model TIMER focuses on long-term trends in energy supply and demand. It was mainly developed for analysing climate mitigation strategies and has also been used to explore other sustainability issues. These characteristics impose some limitations on the model. Firstly, the model cannot be used to examine macro-economic consequences of mitigation strategies, such as GDP losses, because other aspects of the economy are not included. Secondly, the strategies depicted by the model are not necessarily optimal from an inter-temporal perspective because as a simulation model, there is no information on future development in a scenario (myopic). Instead, decisions are made on the basis of available model information at that time in the scenario. Finally, although the model has been used to analyse sustainability issues other than climate change, still much less options have been included to explore such policies (see Section 8.2).

3. Key publications

Van Vuuren DP. (2007). Energy systems and climate policy: Long-term scenarios for an uncertain future, PhD thesis, Utrecht University, Utrecht.

De Vries HJM, Van Vuuren DP, Den Elzen MGJ and Janssen MA (2001). The targets image energy model regional (TIMER) -Technical documentation. PBL Netherlands Environmental Assessment Agency (formerly MNP), Bilthoven/The Hague www.pbl.nl/en.

4.1.1 Energy demand

Detlef van Vuuren, Bas van Ruijven, Bastien Girod, Vassilis Daioglou, Oreane Edelenbosch, Sebastiaan Deetman

Key policy issues

- How will energy demand evolve particularly in emerging and medium- and low-income economies?
- What is the mix of end-use energy carriers to meet future energy demand?
- How can energy efficiency contribute to reducing the growth rate of energy demand and mitigate pressures on the global environment?

1. Introduction

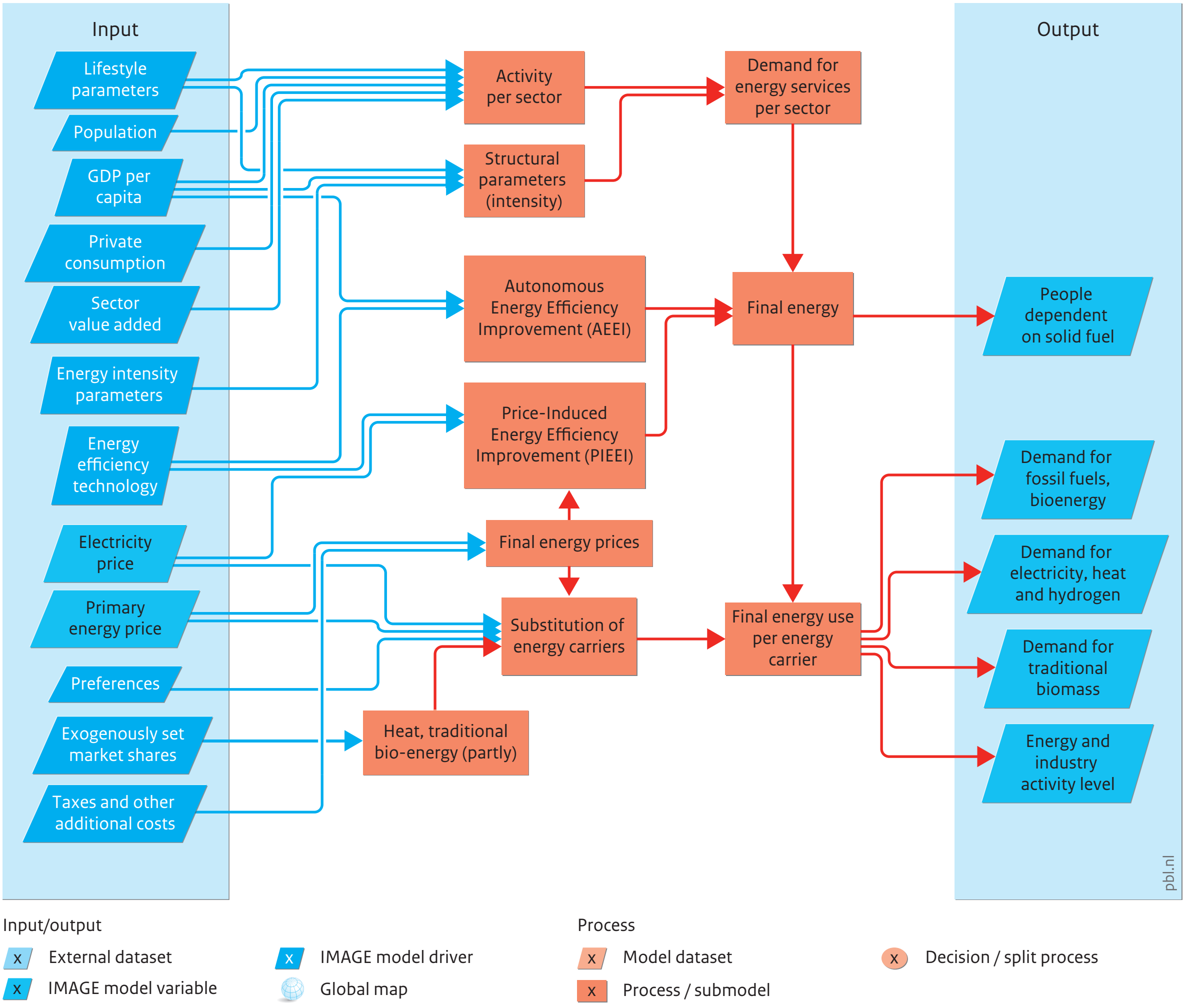
Global energy use has increased rapidly since the industrial revolution. For a historical perspective, most increases have occurred in high-income regions but more recently, the largest increase is in emerging economies. With the aspirations for income growth in medium- and low-income countries, energy demand is to be expected to grow in the coming decades, with major implications for sustainability.

In the TIMER energy demand module, final energy demand is simulated as a function of changes in population, economic activity and energy intensity (Figure 4.1.1.1). Five economic sectors are considered: industry; transport; residential; public and private services; and other sectors mainly agriculture. In each sector, final energy use is driven by the demand for energy services, such as motor drive, mass displacement, chemical conversions, lighting, heating and cooling. Energy demand is considered as a function of three groups of parameters and processes:

- activity data, for example on population and income, and more explicit activity indicators, such as steel production;
- long-term trends that determine the intensity of use, for example, economic structural change (SC), autonomous energy efficiency improvement (AEEI) and price-induced energy efficiency improvement (PIEEI);
- price-based fuel substitution (the choice of energy carrier on the basis of its relative costs).

These factors are implemented in different ways in the various sectors. In some sectors, a detailed end-use service-oriented modelling approach is used while in other sectors, the description is more generic and aggregate. Energy prices link the demand module with other parts of the energy model, as they respond dynamically to changes in demand, supply and conversion.

Figure 4.1.1.1
TIMER model, energy demand module



Source: PBL 2014

Some sectors are represented in a generic way as shown here, the sectors transport, residential and heavy industry are modelled in specific modules. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.1.1.1).

2. Model description

The energy demand module has aggregated formulations for some sectors and more detailed formulations for other sectors. In the description that follows, the generic model is presented which is used for the service sector, part of the industry sector (light) and in the category other sectors. Next, the more technology detailed sectors of residential energy use, heavy industry and transport are discussed in relation to the elements of the generic model.

In the generic module, demand for final energy is calculated for each region (R), sector (S) and energy form (F, heat or electricity) according to:

$$FE_{R,S,F} = \frac{POP_R * (ACT_{R,S} / POP_R) * SC_{R,S,F} * AEEI_{R,S,F} * PIEEI_{R,S,F}}{\sum_F \eta_{R,S,F} * MS_{R,S,F}} \qquad (4.1.1.1)$$

in which FE represents final energy, POP represents population, ACT/POP the sectoral activity per capita, SC a factor capturing intra-sectoral structural change, AEEI the autonomous energy efficiency improvement and PIEEI the price-induced energy efficiency improvement. In the denominator, η is the end-use efficiency of energy carriers used, for example in boilers and stoves, and MS represents the share of each energy carrier. Population and economic activity levels are exogenous inputs into the module. Each of the other dynamic factors in equation 1 are briefly discussed below.

Structural change (SC)
In each sector, the mix of activities changes as a function of development and time. These changes, referred to as structural change, may influence the energy intensity of a sector. For instance, using more private cars for transport instead of buses tends to increase energy intensity. Historically, in several sectors, as a consequence of the structural changes in the type of activities an increase in energy intensity can be observed followed by a decrease. Evidence of this trend is more convincing in industry with shifts from very basic to heavy industry and finally to industries with high value-added products than in other sectors, such as transport where historically, energy intensity has mainly been increasing (De Vries et al., 2001).

Based on the above, in *generic model formulations*, energy intensity is driven by income, assuming a peak in energy intensity, followed by saturation of energy demand at a constant per capita energy service level. In the calibration process, the choice of parameters may lead, for instance, to a peak in energy intensity higher than current income levels. In the *technology-detailed* energy demand (see below), structural change is captured by other equations that describe the underlying processes explicitly (e.g., modal shift in transport).

Autonomous Energy Efficiency Increase (AEEI)
This is a multiplier used in the *generic energy demand module* to account for efficiency improvement as a result of technology improvement, independent of prices. In general, current appliances are more efficient than those available in the past.

The autonomous energy efficiency increase for new capital is a fraction (f) of the economic growth rate based on the formulation of Richels et al. (2004). The fraction varies between 0.45 and 0.30 (based on literature data) and is assumed to decline with time because the scope for further improvement is assumed to decline. Efficiency improvement is assumed for new capital. Autonomous increase in energy efficiency for the average capital stock is calculated as the weighted average value of the AEEI values of the total in capital stock, using the vintage formulation. In the *technology-detailed submodules*, the autonomous energy efficiency increase is represented by improvement in individual technologies over time.

Price-Induced Energy Efficiency Improvement (PIEEI)
This multiplier is used to describe the effect of rising energy costs in the form of induced investments in energy efficiency by consumers. It is included in the *generic formulation* using an energy conservation cost curve. In the *technology-detailed submodules*, this multiplier is represented by competing technologies with different efficiencies and costs.

Substitution
Demand for secondary energy carriers is determined on the basis of demand for energy services and the relative prices of the energy carriers. For each energy carrier, a final efficiency value (η) is assumed to account for differences between energy carriers in converting final energy into energy services. The indicated market share (IMS) of each fuel is determined using a multinomial logit model that assigns market shares to the different carriers (i) on the basis of their relative prices in a set of competing carriers (j).

$$MS_i = \exp(\lambda x_i) / \sum_j \exp(\lambda c_j) \qquad (4.1.1.2)$$

MS is the market share of different energy carriers or technologies and c is their costs. In this equation, λ is the so-called logit parameter, determining the sensitivity of markets to price differences.

The equation takes account of direct production costs and also energy and carbon taxes and premium values. The last two reflect non-price factors determining market shares, such as preferences, environmental policies, infrastructure (or the lack of infrastructure) and strategic considerations. The premium values are determined in the model calibration process in order to correctly simulate historical market shares on the basis of simulated price information. The same parameters are used in scenarios to simulate the assumption on societal preferences for clean and/or convenient fuels. However, the market shares of traditional biomass and secondary heat are determined by exogenous scenario parameters (except for the residential sector discussed below). Non-energy use of energy carriers is modelled on the basis of exogenously assumed intensity of representative non-energy uses (chemicals) and on a price-driven competition between the various energy carriers (Daioglou et al., submitted).

Heavy industry

The heavy industry submodule was included for the steel and cement sectors (Van Ruijven et al., 2013). These two sectors represented about 8% of global energy use and 13% of global anthropogenic greenhouse gas emissions in 2005. The generic structure of the energy demand module was adapted as follows:

- Activity is described in terms of production of tonnes cement and steel. The regional demand for these commodities is determined by a relationship similar to the formulation of the structural change discussed above. Both cement and steel can be traded but this is less important for cement. Historically, trade patterns have been prescribed but future production is assumed to shift slowly to producers with the lowest costs.
- The demand after trade can be met from production that uses a mix of technologies. Each technology is characterised by costs and energy use per unit of production, both of which decline slowly over time. The actual mix of technologies used to produce steel and cement in the model is derived from a multinominal logit equation, and results in a larger market share for the technologies with the lowest costs. The autonomous improvement of these technologies leads to an autonomous increase in energy efficiency. The selection of technologies represents the price-induced improvement in energy efficiency. Fuel substitution is partly determined on the basis of price, but also depends on the type of technology because some technologies can only use specific energy carriers (e.g., electricity for electric arc furnaces).

Transport

The transport submodule consists of two parts - passenger and freight transport. A detailed description of the passenger transport (TRAVEL) is provided by Girod et al. (2012). There are seven modes - foot, bicycle, bus, train, passenger vehicle, high-speed train, and aircraft. The structural change (SC) processes in the transport module are described by an explicit consideration of the modal split. Two main factors govern model behaviour, namely the near-constancy of the travel time budget (TTB), and the travel money budget (TMB) over a large range of incomes. These are used as constraints to describe transition processes among the seven main travel modes, on the basis of their relative costs and speed characteristics and the consumer preferences for comfort levels and specific transport modes.

The freight transport submodule is a simpler structure. Service demand is projected with constant elasticity of the industry value added for each transport mode. In addition, demand sensitivity to transport prices is considered for each mode, depending on its share of energy costs in the total service costs.

The efficiency changes in both passenger and freight transport represent the autonomous increase in energy efficiency, and the price-induced improvements in energy efficiency improvement parameters. These changes are described by substitution processes in explicit technologies, such as vehicles with different energy efficiencies, costs and fuel type characteristics compete on the basis of preferences and total passenger-kilometre costs, using a multinomial logit equation. The efficiency of the transport fleet is determined by a weighted average of the full fleet (a vintage model, giving an explicit description of the efficiency in all single years). As each type of vehicle is assumed to use only one fuel type, this process also describes the fuel selection.

Residential energy use

The residential submodule describes the energy demand from household energy functions of cooking appliances, space heating and cooling, water heating and lighting. These functions are described in detail elsewhere (Van Ruijven et al., 2011; Daioglou et al., 2012).

Structural change in energy demand is presented by modelling end-use household functions:

- Energy service demand for space heating is modelled using correlations with floor area, heating degree days and energy intensity, the last including building efficiency improvements.
- Hot water demand is modelled as a function of household income and heating degree days.
- Energy service demand for cooking is determined on the basis of an average constant consumption of 3 MJ_{UE}/capita/day.
- Energy use related to appliances is based on ownership, household income, efficiency reference values, and autonomous and price-induced improvements. Space cooling follows a similar approach, but also includes cooling degree days (Isaac and Van Vuuren, 2009).
- Electricity use for lighting is determined on the basis of floor area, wattage and lighting hours based on geographic location.

Efficiency improvements are included in different ways. Exogenously driven energy efficiency improvement over time is used for appliances, light bulbs, air conditioning, building insulation and heating equipment, Price-induced energy efficiency improvements (PIEEI) occur by explicitly describing the investments in appliances with a similar performance level but with different energy and investment costs. For example, competition between incandescent light bulbs and more energy-efficient lighting is determined by changes in energy prices.

The model distinguishes five income quintiles for both the urban and rural population. After determining the energy demand per function for each population quintile, the choice of fuel type is determined on the basis of relative costs. This is based on a multinomial logit formulation for energy functions that can involve multiple fuels, such as cooking and space heating. In the calculations, consumer discount rates are assumed to decrease along with household income levels, and there will be increasing appreciation of clean and convenient fuels (Van Ruijven et al., 2011). For developing countries, this endogenously results in the substitution processes described by the energy ladder. This refers to the progressive use of modern energy types as incomes grow, from traditional bioenergy to coal and kerosene, to energy carriers such as natural gas, heating oil and electricity.

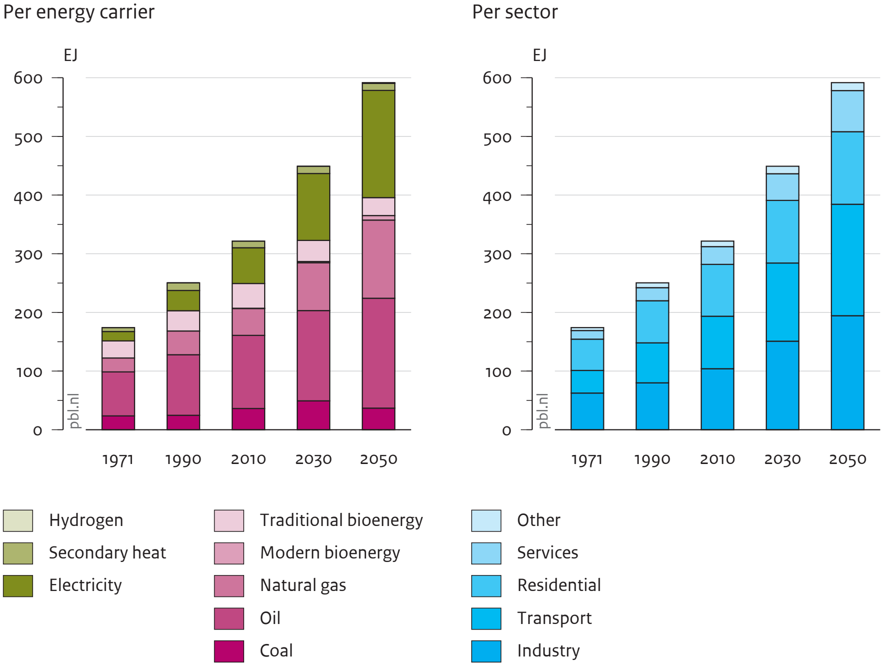
The residential submodule also includes access to electricity and the associated investments (Van Ruijven et al., 2012). Projections for access to electricity are based on an econometric analysis that found a relation between level of access, and GDP per capita and population density. The investment model is based on population density on a 0.5x0.5 degree grid, from which a stylised power grid is derived and analysed to determine investments in low-, medium- and high-voltage lines and transformers.

3. Policy issues

Baseline developments

The model shows that under a typical baseline scenario such as the one of the Rio+20 study, energy demand is projected to grow significantly during the 21st century (Figure 4.1.1.2). Most growth will be driven by an increase in energy use in low-income countries. Per capita use in high-income countries is projected to remain more or less constant, consistent with recent historical trends. The increase in energy demand in the first half of the century will be mostly met by fossil fuels and electricity. In this model simulation, hydrogen becomes competitive in the transport sector in the second half of the century, as a result of increasing oil prices and the assumed progress in hydrogen technologies. An alternative assumption could result in a similar role for electricity.

Figure 4.1.1.2
Global final energy demand under a baseline scenario



Source: PBL 2014

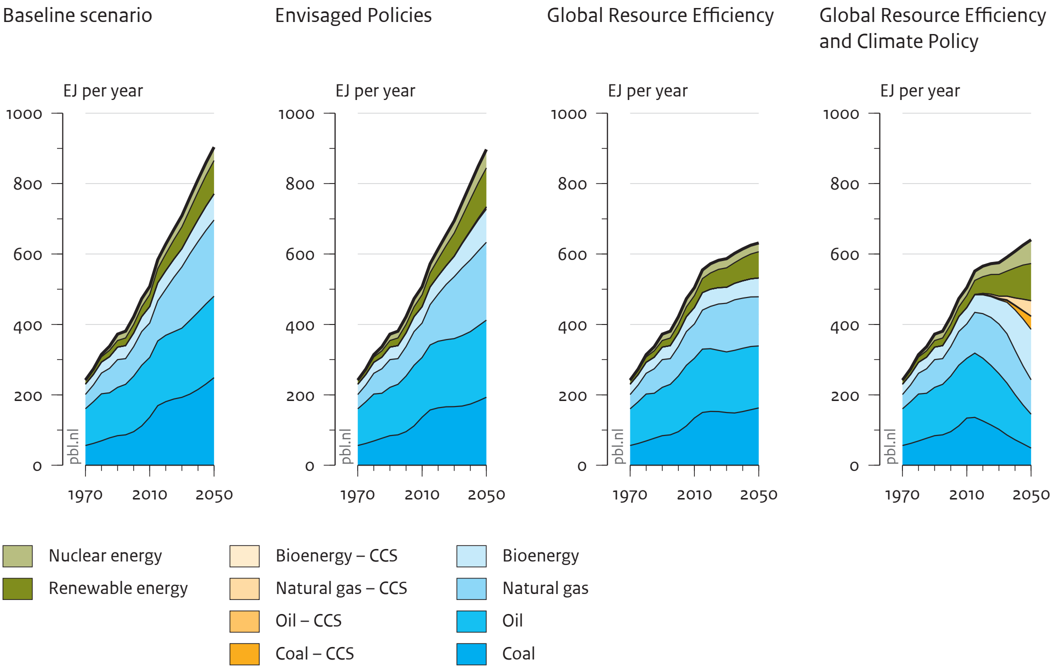
Between 2010 and 2050 energy demand for transport and industry, and for natural gas and electricity contribute most to the overall increase.

Policy interventions

Various policy interventions can be implemented in the energy demand submodules in different ways:

- Energy tax and carbon tax. This changes the prices for the energy carriers, and influences the choice of technology.
- Discount rate/payback time. In the residential submodule , the perceived costs of capital (discount rate) influence the extent of energy efficiency improvement (PIEEI) and the choice of fuel and/or technology in the residential submodule.
- Preferences. Fuel choice can be influenced by correction factors, representing aspects that influence fuel choice but are not incorporated in the price, such as fuel characteristics (e.g., cleanliness, availability), comfort and speed considerations, and infrastructure.
- Efficiency standards. Such improvements can be introduced for the submodules that focus on specific technologies, for example, in transport, heavy industry and households.

Figure 4.1.1.3
Global primary energy use under baseline and policy scenarios



Source: Van den Berg et al. 2011

The 'envisaged policies' scenario includes currently planned policies, the 'global resource efficiency' scenario assumes ambitious energy efficiency policies, and the 'global resource efficiency and climate policy' scenario additionally assumes policies to meet the 2 °C target. Total primary energy use could be significantly reduced by policies on energy efficiency, whereas additional climate policy would mostly affect the type of resources used. (Van den Berg et al., 2011)

– Enforced market shares of fuel types. Such an analysis could, for instance, provide insight into the implications in the model of increasing the use of biofuels, electricity or hydrogen (Van Ruijven et al., 2007).

The PBL study Resource Efficiency (Van den Berg et al., 2011) provides an example of how TIMER can be used to explore the impact of radically improving energy efficiency (Figure 4.1.1.3). The study included an accelerated trend to best available technologies in iron and steel production and other industries, most efficient passenger vehicles and aircraft, a moderate shift from aircraft to high-speed trains, and building highly efficient housing (mostly insulation measures). The study also assumed that newly installed power plants will be based on the best available technologies. The measures in this global energy efficiency scenario will considerably reduce energy use than under the baseline scenario. Primary energy consumption will be reduced by about 30% by 2050.

4. Data, uncertainties and limitations

Data

The energy demand module has been calibrated for the 1971–2007 period in order to reproduce historical trends in fuel and electricity use (see papers on individual model components, such as Van Ruijven et al., 2010a). Using the historical input data on population and value added and the calculated energy prices as given, other drivers and model parameters were varied systematically within the range of values derived from the literature, in order to improve the fit (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The primary data source on energy use was the International Energy Agency (IEA). These data were complemented with data from other sources, such as steel and cement demand and production, and transport data from as described in the references of the different model components. The residential submodule uses data from national statistical agencies and household surveys (Van Ruijven et al., 2010a).

Uncertainties

The main uncertainties in modelling energy demand relate to the interpretation of historical trends, for instance, on the role of structural change, autonomous energy efficiency increases and price-induced efficiency improvements and their projection for the future (Van Vuuren et al., 2008).

Two uncertainties are the existence of saturation levels and the potential for efficiency increases. The representation in TIMER is based on the assumption that demand for energy services tends to become saturated at some point. This is based on physical considerations and historical trends in sectors, such as residential energy use. However, economic models assume that income and energy use remain coupled, often even at constant growth elasticities. Evidence for a constant growth can also be found in some sectors, notably transport and services.

In deciding between these different dynamics, the extent to which historical trends would be the best guide for the future is also unclear. A similar issue concerns the role of energy efficiency. Many techno-economic analyses of efficiency potential suggest large possibilities at rather low payback times. However, from a historical perspective, investments in efficiency have been significantly lower than optimal for cost minimisation. Other factors must be assumed to play a role in the form of perceived transaction costs. A critical issue is whether this efficiency potential could be exploited in the future.

In the model calibration, there is a large degree of freedom in parameter setting so that results fit historical observations. A method has been developed to identify the implications of different outcomes of model calibrations and has been applied to the transport and residential submodules (Van Ruijven et al., 2010a; Van Ruijven et al., 2010b).

The starting point is that insufficient data are available to fully understand historic trends and calibrate global energy models. TIMER has room for different sets of parameter values that simulate historical energy use equally well, but reflect different historical interpretations and result in different future projections. The recent trend to replace some energy models by a description of end-use functions and applying physical considerations will reduce some uncertainties as this enables better estimation of reasonable saturation levels. However, this method suffers from the fact that new energy functions may be developed in the future that could increase energy demand.

Limitations

The main limitations of the TIMER energy demand model are listed in the introduction to the model. A critical factor in modelling energy demand is the level of detail, given the large number of relevant technologies. TIMER uses an intermediate approach, in which some key technologies are modelled explicitly, and others are included implicitly. For more detailed estimates of the potential of energy efficiency, it would be more appropriate to use a different model.

5. Key publications

Daioglou V, Van Ruijven BJ and Van Vuuren DP. (2012). Model projections for household energy use in developing countries. *Energy* 37(1), pp. 601–615, DOI: 10.1016/j.energy.2011.10.044.

Girod B, Van Vuuren DP and Deetman S. (2012). Global travel within the 2 degree climate target. *Energy Policy* 45, pp. 152–166, DOI: 10.1016/j.enpol.2012.02.008.

Van Ruijven BJ, Schers J and Van Vuuren DP. (2012). Model-based scenarios for rural electrification in developing countries. *Energy* 38(1), pp. 386–397, DOI: 10.1016/j.energy.2011.11.037.

6. Input/Output Table

Table 4.1.1.1
Input in and output from the energy demand module of TIMER

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Population	Number of people per region.	3
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	3
Sector value added	Value Added for economic sectors: Industry (IVA), Services (SVA) and Agriculture (AVA). These variables are used in IMAGE to indicate economic activity.	3
Private consumption	Private consumption reflects expenditure on private household consumption. It is used in IMAGE as a driver of energy.	3
Energy efficiency technology	Model assumptions determining future development of energy efficiency.	3
Taxes and other additional costs	Taxes on energy use, and other additional costs	3
Energy intensity parameters	Set of parameters determining the energy use per unit of economic activity (in absence of technical energy efficiency improvements).	3
Lifestyle parameters	Lifestyle parameters influence the relationship between economic activities and demand for energy.	3
Preferences	Non-price factors determining market shares, such as preferences, environmental policies, infrastructure and strategic considerations, used for model calibration.	3
Primary energy price	The price of primary energy carriers based on production costs.	4.1.3
Electricity price	The price of electricity.	4.1.2
External datasets		
Exogenously set market shares	Market shares of traditional biomass and secondary heat, for all demand sectors except the residential sector, exogenous scenario parameter.	IEA

Output	Description	Use (section)
People dependent on solid fuel	Proportion of population using traditional biomass and coal for cooking and heating.	7.7
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	5.2
Demand for electricity, heat and hydrogen	The demand for production of electricity, heat and hydrogen.	4.1.2
Demand traditional biomass	Regional demand for traditional bioenergy.	4.2.2
Demand for fossil fuels and bioenergy	The demand for the production of fossil fuels and bioenergy.	Final output

4.1.2 Energy conversion

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Key policy issues

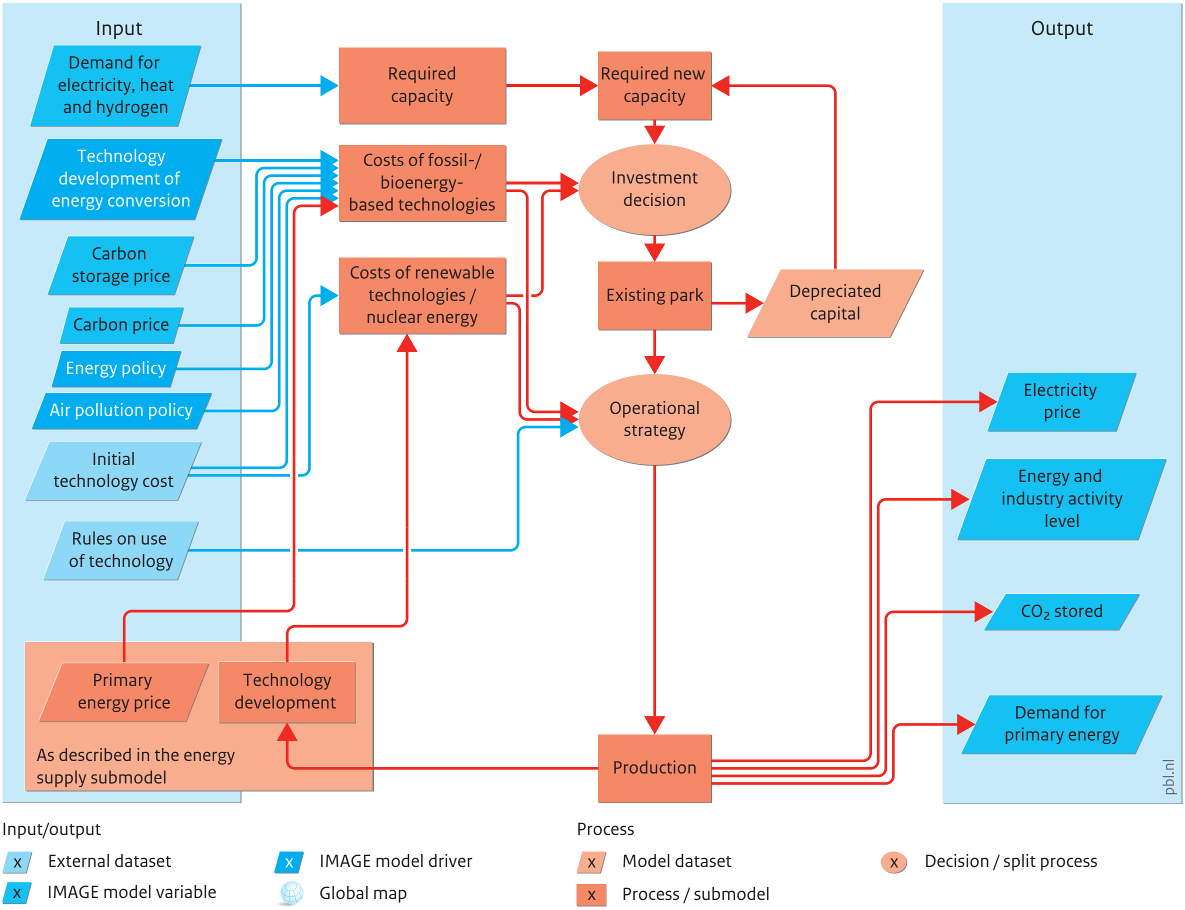
- What is the potential role of the energy conversion sector, particularly in power production, in achieving a more sustainable energy system?
- What are the potential roles of individual technologies, such as carbon capture and storage (CCS), nuclear power, hydrogen and renewable energy?

1. Introduction

Energy from primary sources often has to be converted into secondary energy carriers that are more easily accessible for final consumption, for example the production of electricity and hydrogen, oil products from crude oil in refineries, and fuels from biomass. Studies on transitions to more sustainable energy systems also show the importance of these conversions for the future.

The energy conversion module of TIMER simulates the choices of input energy carriers in two steps. In the first step, investment decisions are made on the future generation mix in terms of newly added capital. In the second step, the actual use of the capacity in place depends on a set of model rules that determine the purpose and how frequently the different types of power plants are used (baseload/peakload). The discussion focuses on the production of electricity and hydrogen. Other conversion processes have only be implemented in the model by simple multipliers, as they mostly convert energy from a single primary source to one secondary energy carrier. These processes are discussed in Section 4.1.3, Energy Supply.

Figure 4.1.2.1
TIMER model, electricity module



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.1.2.1).

2. Model description

TIMER includes two main energy conversion modules: electric power generation and hydrogen generation. Below, electric power generation is described in detail. In addition, the key characteristics of the hydrogen generation model, which follows a similar structure, are presented.

Electric power generation

As shown in Figure 4.1.2.1, two key elements of the electric power generation are the investment strategy and the operational strategy in the sector. A challenge in simulating electricity production in an aggregated model is that in reality electricity production depends on a range of complex factors, related to costs, reliance, and the time required to switch on technologies. Modelling these factors requires a high level of detail and thus IAMs such as TIMER concentrate on introducing a set of simplified, meta relationships (Hoogwijk, 2004; Van Vuuren, 2007).

Total demand for new capacity

The electricity capacity required to meet the demand per region is based on a forecast of the maximum electricity demand plus a reserve margin of about 10% (including the capacity credit assigned to different forms of electricity generation). Maximum demand is calculated on the basis of an assumed monthly shape of the load duration curve (LDC) and the gross electricity demand. The latter comprises the net electricity demand from the end-use sectors plus electricity trade and transmission losses (LDC accounts for characteristics such as cooling and lighting demand). The demand for new generation capacity is the difference between the required and existing capacity. Power plants are assumed to be replaced at the end of their lifetime, which varies from 30 to 50 years, depending on the technology and is currently fixed in the model.

Decisions to invest in specific options

In the model, the decision to invest in generation technologies is based on the price of electricity (in USD/kWhe) produced per technology, using a multinomial logit equation that assigns larger market shares to the lower cost options. The specific cost of each option is broken down into several categories: investment or capital cost (USD/kWe); fuel cost (USD/GJ); operational and maintenance costs (O&M); and other costs (see further). The exception is hydropower capacity, which is exogenously prescribed, because large hydropower plants often have additional functions such as water supply and flood control. In the equations, some constraints are added to account for limitations in supply, for example restrictions on biomass availability. The investment for each option is given as the total investment in new generation capacity and the share of each individual technology determined on the basis of price and preference.

Operational strategy

Use of power plants is based on operational costs, with low-cost technologies assumed to be used most often. This implies that capital-intensive plants with low operational costs, such as renewable and nuclear energy, operate as many hours as possible. To some degree, this is also true for other plants with low operational costs, such as coal.

The operational decision is presented in the following three steps:

1. Renewable sources PV and wind are assigned, followed by hydropower, because these options have the lowest operational costs;
2. The peak load capacity (period of high electricity demand) is assigned on the basis of the operational costs of each available plant and the ability of these plants to provide peak load capacity;
3. Base load (period of medium to low energy demand) is assigned on the basis of the remaining capacity (after steps 1 and 2), operational costs and the ability of options to provide the base load capacity.

Fossil fuel and bioenergy power plants

A total of 20 types of power plants generating electricity using fossil fuels and bioenergy are included. These power plants represent different combinations of conventional technology, such as gasification and combined cycle (CC) technology; combined heat and power (CHP); and carbon capture and storage (CCS;(Hendriks et al., 2004b). The specific capital costs and thermal efficiencies of these types of plants are determined by exogenous assumptions that describe the technological progress of typical components of these plants:

- For conventional power plants, the coal-fired plant is defined in terms of overall efficiency and investment cost. The characteristics of all other conventional plants (using oil, natural gas or bioenergy) are described in the investment differences for desulphurisation, fuel handling and efficiency.
- For Combined Cycle (CC) power plants, the characteristics of a natural gas fired plant are set as the standard. Other CC plants (fueled by oil, bioenergy and coal after gasification) are defined by indicating additional capital costs for gasification, efficiency losses due to gasification, and operation and maintenance (O&M) costs for fuel handling.
- Power plants with carbon-capture-and-storage systems (CCS) are assumed to be CC plants, but with fuel-specific lower efficiency and higher investment and O&M costs (related to capture and storage).
- The characteristics of combined-heat-and-power plants (CHP) are similar to those of other plants, but with an assumed small increase in capital costs, in combination with a lower efficiency for electric conversion and an added factor for heat efficiency.

The cost of one unit electricity generated is equal to the sum of the capital cost, operational and maintenance costs (O&M), fuel cost, and CO_2 storage cost.

Solar and wind power

The costs of solar and wind power in the model are determined by learning and depletion dynamics. For renewable energy, costs relate to capital, O&M and system integration. The capital costs mostly relate to learning and depletion processes. Learning is represented by in learning curves (Box 4.1.3.1); depletion by long-term cost–supply curves.

The additional system integration costs relate to curtailed electricity (if production exceeds demand and the overcapacity cannot be used within the system), backup capacity; and additional required spinning reserve. The last items are needed to avoid loss of power if the supply of wind or solar power drops suddenly, enabling a power scale up in a relatively short time, in power stations operating below maximum capacity (Hoogwijk, 2004).

To determine curtailed electricity, the model compares 10 points on the load-demand curve at the overlap between demand and supply. For both wind and solar power, a typical load supply curve is assumed (see Hoogwijk, 2004). If supply exceeds demand, the overcapacity in electricity is assumed to be discarded, resulting in higher production costs.

Because wind and solar power supply is intermittent (variable and thus not reliable), the model assumes that backup capacity needs to be installed. It is assumed that no backup is required for first 5% penetration of the intermittent capacity. However, for higher levels of penetration, the effective capacity (degree to which operators can rely on plants producing at a specific time) of intermittent resources is assumed to decrease. This is referred to as the capacity factor. This decrease leads to the need for backup power by low-cost options, such as gas turbines, the cost of which is allocated to the intermittent source.

The required spinning reserve of the power system is the capacity that can be used to respond to a rapid increase in demand. This is assumed to be 3.5% of the installed capacity of a conventional power plant. If wind and solar power further penetrate the market, the model assumes an additional, required spinning reserve of 15% of the intermittent capacity (after subtraction of the 3.5% existing capacity). The related costs are allocated to the intermittent source.

Nuclear power

The costs of nuclear power also include capital, O&M and nuclear fuel costs. Similar to the renewable energy options, technology improvement in nuclear power is described via a learning curve (costs decrease with cumulative installed capacity). Fuel costs increase as a function of depletion. Fuel costs are determined on the basis of the estimated extraction costs for uranium and thorium resources, see Section 4.1.3: Energy Supply. A small trade model for these fission fuels is included.

Hydrogen generation

The structure of the hydrogen generation submodule is similar to that for electric power generation (Van Ruijven et al., 2007) but with following differences:

- There are only eleven supply options for hydrogen production from coal, oil, natural gas and bioenergy, with and without carbon capture and storage (8 plants); hydrogen production from electrolysis, direct hydrogen production from solar thermal processes; and small methane reform plants.
- No description of preferences for different power plants is taken into account in the operational strategy. The load factor for each option equals the total production divided by the capacity for each region.
- Intermittence does not play an important role because hydrogen can be stored to some degree. Thus, there are no equations simulating system integration.
- Hydrogen can be traded. A trade model is added, similar to those for fossil fuels described in Section 4.1.3: Energy Supply.

3. Policy issues

Baseline developments

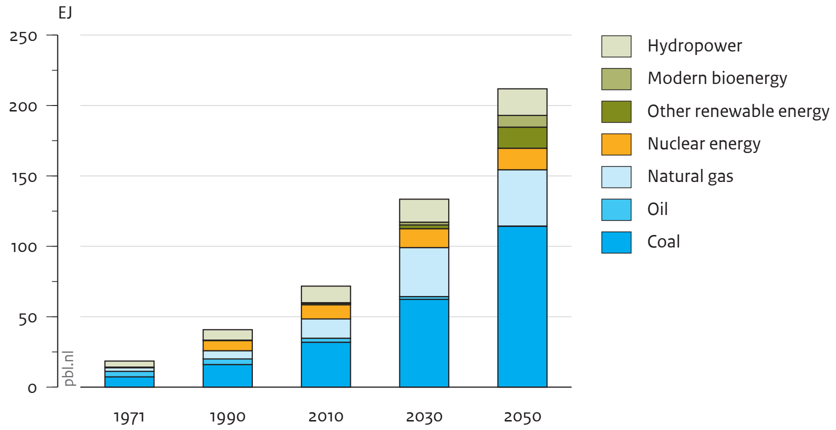
The energy conversion module may be used to generate scenarios with and without climate policy. The results for a typical baseline scenario are shown in Figure 4.1.2.2. At present, coal is the main feedstock for power generation globally. In high-income regions, coal faces competition from natural gas, but in emerging economies, such as China and India, coal is still by far the largest resource used. The baseline scenario projects coal use to expand. The underlying reasons for this expansion are the rapid increase in electricity use in emerging economies, and the stronger price increases for natural gas than for coal. The latter, clearly, also depends on the uncertainty in future natural gas supply. On a global scale, wind power and biomass-fired power plants are rapidly expanding in total capacity.

Policy interventions

IMAGE model simulations include several types of policy interventions that may influence electricity and hydrogen production:

- Carbon tax: this measure is usually implemented on an economy-wide scale and has strong influence on investment and operational strategies in the power system.
- An imposed minimum or maximum share per energy source - renewable energy, CCS technology, nuclear power and other forms of power generation. This would directly influence the capacity installed for each option.
- Promoting the use of electricity and hydrogen on end-user level. With the high flexibility in the choice of feedstock in these systems, large proportions of electricity and hydrogen use in final energy would increase the ability of the total system to reduce greenhouse gas emissions.
- The exclusion of certain power-generation options for environmental and/or security reasons (Kruyt et al., 2009).

Figure 4.1.2.2
Electricity production, per energy carrier under a baseline scenario



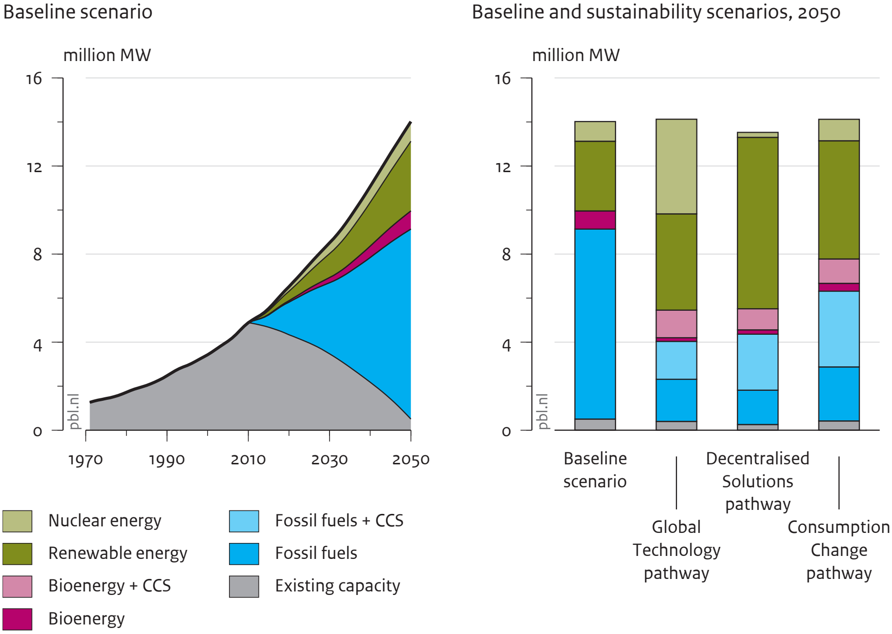
Source: PBL 2014

Increase in primary energy demand for electricity production is dominated by coal, despite a rapid growth of renewable energy.

Model analyses show that a high proportion of emission reductions would be achieved through supply side changes. The capacity for different supply-side options under the baseline scenario and various pathways consistent with the 2 °C climate change target are presented in Figure 4.1.2.3.

The proportion of unabated fossil fuel use is still 80% of total primary energy under the baseline scenario (see above) but by 2050, this would need to be around 15 to 20% according to the 2 °C scenarios. The results show that pathways can be identified in which the remaining energy comes from bioenergy, other renewable energy, nuclear energy, and from fossil-fuel energy combined with CCS. There is flexibility in the choice of these options, as illustrated in the *Decentralised Solutions* and *Global Technology* pathways with different patterns for nuclear power and renewable energy. In the IMAGE framework under nearly all scenarios, the combination of bioenergy and CCS, and CCS in general, plays a critical role in achieving the 2 °C target.

Figure 4.1.2.3
Global capacity of the power sector



Source: PBL 2012

The large share of conventional coal power in the baseline is replaced by fossil power with CCS and renewable capacity in the sustainability scenarios.

4. Data, uncertainties and limitations

Data

The main data sources for the energy conversion module in TIMER are shown below (Table 4.1.2.2).

Uncertainties

The two main uncertainties are calculation of future energy conversion relating to development rates of the conversion technologies, and the consequences for the electricity system of a high level of market penetration of renewable energy.

TIMER electric power generation submodule has been tested for different levels of market penetration of renewable energy in the United States and western Europe (Hoogwijk et al., 2007). The model was shown to reproduce the behaviour of more detailed models that describe system integration costs. More recent studies seem to suggest that some of the limitations in renewable energy penetration can be overcome at reasonable costs, implying the current description is rather conservative. Integration costs for renewable energy are very uncertain because large shares of market penetration still need to be achieved, except in a few countries. The power system was exposed to all types of technology limitations in experiments run by Van Vliet et al. (2013). These experiments showed that to achieve low stabilisation targets, a large portfolio of mitigation options should be available.

Table 4.1.2.2
Main data sources for the TIMER energy conversion module

Input	Data source
Electricity production and primary inputs	IEA Statistics and Data (IEA, 2012a)
Capacity of different plant types per region	Energy Statistics and Data (Enerdata, 2010b; IEA, 2012a)
Performance of fossil-fuel- and bioenergy-fired plants	Hendriks et al.(2004b)
CCS plants and storage	Hendriks et al.(2004a)
Prices	IEA Statistics and Data (IEA, 2012a)
Hydropower potential	World Energy Council (WEC, 2010)
Solar and wind costs	Hoogwijk et al., (2007)
Nuclear power – technology and resources	WEC (WEC, 2010); MIT (2003)
Hydrogen technologies	Van Ruijven et al., (2007)

Limitations

The model describes long-term trends in the energy system, which implies that the focus is on aggregated factors that may determine future energy demand and supply. However, in energy conversion, many short-term dynamics can be critical for the system, such as system reliability and ability to respond to demand fluctuations. These processes can only be represented in an aggregated global model in terms of meta-formulations, which implies that some of the integration issues regarding renewable energy are still not addressed.

Another limitation is the formulation of primary fossil-fuel conversions in secondary fuels. TIMER currently does not include a module that explicitly describes these processes.

5. Key publications

Hoogwijk M, Van Vuuren D, De Vries B and Turkenburg W. (2007). Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy. *Energy* 32(8), pp. 1381–1402.
Hendriks C, Harmelink M, Burges K and Ransel K (2004b). Power and heat productions: plant developments and grid losses. Ecofys, Utrecht.

6. Input/Output Table

Table 4.1.2.1
Input in and output from the energy conversion module of TIMER

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Air pollution policy	Air pollution policies set to reach emission reduction targets, represented in the model in the form of energy carrier and sector specific emission factors.	3
Energy policy	Policy to achieve energy system objectives, such as energy security and energy access.	3
Technology development of energy conversion	Learning curves and exogenous learning that determine technology development.	3
Demand for electricity, heat and hydrogen	The demand for production of electricity, heat and hydrogen.	4.1.1
Primary energy price	The price of primary energy carriers based on production costs.	4.1.3
Carbon price	Carbon price on the international trading market (in USD2005 per tonne C-eq) calculated from aggregated regional permit demand and supply curves derived from marginal abatement costs.	8.1
Carbon storage price	The costs of capturing and storing CO_2, affecting the use of CCS technology.	4.1.3
External datasets		
Initial technology cost	The costs of energy conversion technologies at the start of the simulation.	Various sources
Rules on use of technology	Rules determining how different types of power plants are used.	Various sources
Output	**Description**	**Use (section)**
Electricity price	The price of electricity.	4.1.1
Demand for primary energy	Total demand for energy production. Sum of final energy demand and energy inputs into energy conversion processes.	4.1.3
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	5.2
CO_2 stored	The amount of CO_2 stored in underground reservoirs by applying CO_2 capture technology.	Final output

4.1.3 Energy supply

Detlef van Vuuren, Bert de Vries, Monique Hoogwijk

Key policy issues

- How can energy resources be exploited to meet future primary energy demand?
- How can energy supply and demand be balanced between world regions, and how will this effect security of supply?
- How rapidly can the transition to more sustainable energy supply be made?

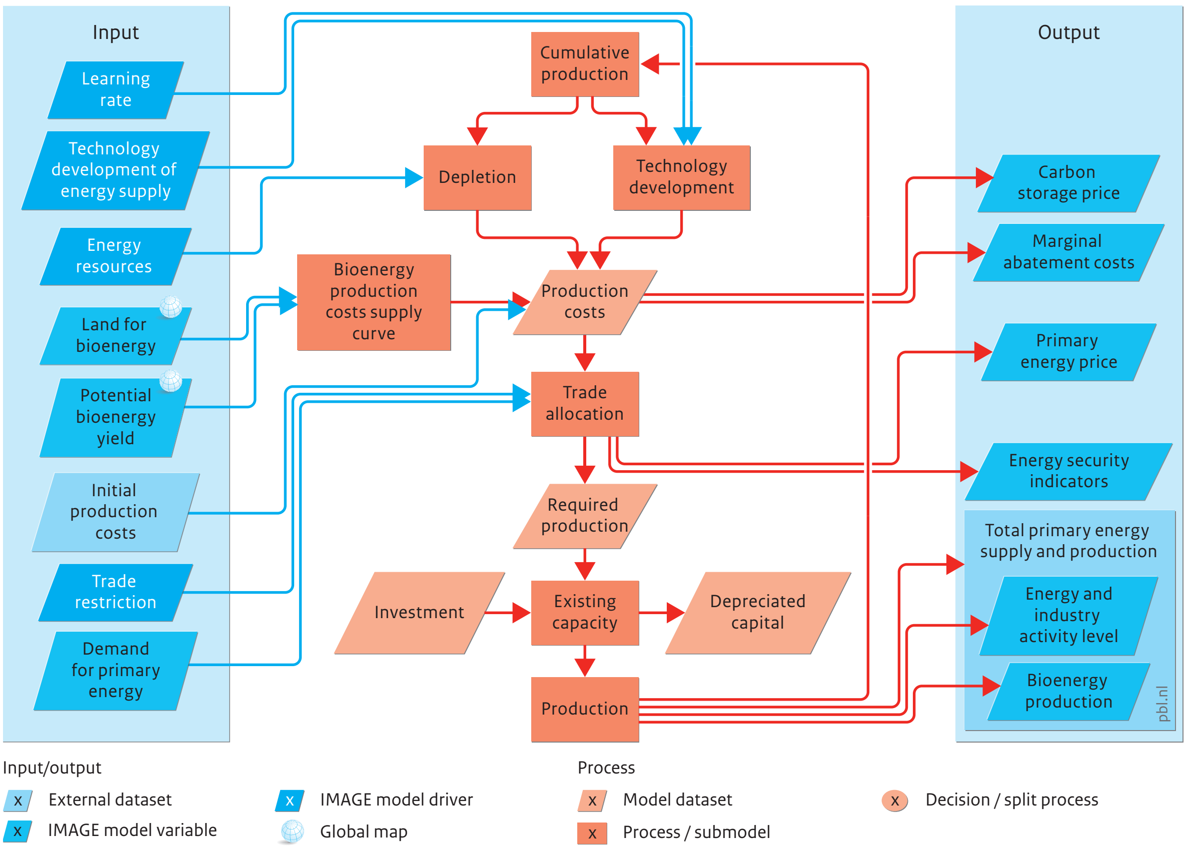
1. Introduction

A key factor in future energy supply is the availability (and depletion) of various resources. One aspect is that energy resources are unevenly spread across world regions and often, poorly matched with regional energy demand. This is directly related to energy security. In representation of energy supply, the IMAGE energy model describes long-term dynamics based on the interplay between resource depletion (upward pressure on prices) and technology development (downward pressure on prices). In the model, technology development is introduced in the form of learning curves for most fuels and renewable options. Costs decrease endogenously as a function of the cumulative energy capacity, and in some cases, assumptions are made about exogenous technology change.

Depletion is a function of either cumulative production or annual production. For example, for fossil-fuel resources and nuclear feedstock, low-cost resources are slowly being depleted, and thus higher cost resources need to be used. In annual production, for example, of renewables, attractive production sites are used first. Higher annual production levels require use of less attractive sites with less wind or lower yields.

It is assumed that all demand is always met. Because regions are usually unable to meet all of their own demand, energy carriers, such as coal, oil and gas, are widely traded. The impact of depletion and technology development lead to changes in primary fuel prices, which influence investment decisions in the end-use and energy-conversion modules. Linkages to other parts of IMAGE framework include available land for bioenergy production, emissions of greenhouse gases and air pollutants (partly related to supply), and the use of land for bioenergy production (land use for other energy forms are not taken into account). Several key assumptions determine the long-term behaviour of the various energy supply submodules and are mostly related to technology development and resource base.

Figure 4.1.3.1
TIMER model, energy supply module



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.1.3.1).

2. Model description

Fossil fuels and uranium

Depletion of fossil fuels (coal, oil and natural gas) and uranium is simulated on the assumption that resources can be represented by a long-term supply cost curve, consisting of different resource categories with increasing cost levels. The model assumes that the cheapest deposits will be exploited first. For each region, there are 12 resource categories for oil, gas and nuclear fuels, and 14 categories for coal.

A key input for each of the fossil fuel and uranium supply submodules is fuel demand (fuel used in final energy and conversion processes). Additional input includes conversion losses in refining, liquefaction, conversion, and energy use in the energy system (Figure 4.1.3.1). These submodules indicate how demand can be met by supply in a region and other regions through interregional trade.

Table 4.1.3.2
Main assumptions on fossil fuel resources (Rogner, 1997; Mulders et al., 2006)

	Oil	Natural gas	Underground coal	Surface coal
Cum. 1970-2005 production	4.4	2.1	1.6	1.1
Reserves	4.8	4.6	23.0	2.2
Other conventional resources	6.6	6.9	117.7	10.0
Unconventional resources (reserves)	2.9	6.9	25.0	233.5
Other unconventional resources	46.2	498.6	1.3	23.0
Total	65.0	519.2	168.6	270.0

Fossil fuel resources are aggregated to five resource categories for each fuel (Table 4.1.3.2). Each category has typical production costs. The resource estimates for oil and natural gas imply that for conventional resources supply is limited to only two to eight times the 1970–2005 production level. Production estimates for unconventional resources are much larger, albeit very speculative. Recently, some of the occurrences of these unconventional resources have become competitive such as shale gas and tar sands. For coal, even current reserves amount to almost ten times the production level of the last three decades. For all fuels, the model assumes that, if prices increase, or if there is further technology development, the energy could be produced in the higher cost resource categories. The values presented in Table 4.1.3.2 represent medium estimates in the model, which can also use higher or lower estimates in the scenarios. The final production costs in each region are determined by the combined effect of resource depletion and learning-by-doing.

Trade

Trade is dealt with in a generic way for oil, natural gas and coal. In the fuel trade model, each region imports fuels from other regions. The amount of fuel imported from each region depends on the relative production costs and those in other regions, augmented with transport costs, using multinomial logit equations. Transport costs are calculated from representative interregional transport distances and time- and fuel-dependent estimates of the costs per GJ per kilometre.

To reflect geographical, political and other constraints in the interregional fuel trade, an additional 'cost' is added to simulate trade barriers between regions (this costs factor is determined by calibration). Natural gas is transported by pipeline or liquid-natural gas (LNG) tanker, depending on distance, with pipeline more attractive for short distances. In order to account for cartel behaviour, the model compares production costs with and without unrestricted trade. Regions that can supply at lower costs than the average production costs in importing regions (a threshold of 60% is used) are assumed to supply oil at a price only slightly below the production costs of the importing regions. Although also this rule is implemented in a generic form for all energy carriers, it is only effective for oil, where the behaviour of the OPEC cartel is simulated to some extent.

Bioenergy

The structure of the biomass submodule is similar to that for fossil fuel supply, but with the following differences (Hoogwijk, 2004):

- Depletion of bioenergy is not governed by cumulative production but by the degree to which available land is used for commercial energy crops.
- The total amount of potentially available bioenergy is derived from bioenergy crop yields calculated on a 0.5x0.5 degree grid with the IMAGE crop model (Section 6.2) for various land-use scenarios for the 21st century. Potential supply is restricted on the basis of a set of criteria, the most important of which is that bioenergy crops can only be on abandoned agricultural land and on part of the natural grassland. The costs of primary bioenergy crops (woody, maize and sugar cane) are calculated with a Cobb-Douglas production function using labour , land rent and capital costs as inputs. The land costs are based on average regional income levels per km^2, which was found to be a reasonable proxy for regional differences in land rent costs. The production functions are calibrated to empirical data (Hoogwijk, 2004).
- The model describes the conversion of biomass (including residues, in addition to wood crops, maize and sugar cane) to two generic secondary fuel types: bio-solid fuels used in the industry and power sectors; and liquid fuel used mostly in the transport sector.
- The trade and allocation of biofuel production to regions is determined by optimisation. An optimal mix of bio-solid and bio-liquid fuel supply across regions is calculated, using the prices of the previous time step to calculate the demand.

Box 4.1.3.1: Learning by doing

An important aspect of TIMER is the endogenous formulation of technology development, on the basis of learning by doing, which is considered to be a meaningful representation of technology change in global energy models (Azar and Dowlatabadi, 1999; Grubler et al., 1999; Wene, 2000). The general formulation of 'learning by doing' in a model context is that a cost measure y tends to decline as a power function of an accumulated learning measure, where n is the learning rate, Q the cumulative capacity or output, and C is a constant:

$$Y = C * Q^{-n}$$

Often n is expressed by the progress ratio p, which indicates how fast the costs metric Y decreases with doubling of Q ($p=2^{-n}$). Progress ratios reported in empirical studies are mostly between 0.65 and 0.95, with a median value of 0.82 (Argotte and Epple, 1990).

In TIMER, learning by doing influences the capital output ratio of coal, oil and gas production, the investment cost of renewable and nuclear energy, the cost of hydrogen technologies, and the rate at which the energy conservation cost curves decline. The actual values used depend on the technologies and the scenario setting. The progress ratio for solar/wind and bioenergy has been set at a lower level than for fossil-based technologies, based on their early stage of development and observed historical trends (Wene, 2000).

There is evidence that, in the early stages of development, p is higher than for technologies in use over a long period of time. For instance, values for solar energy have typically been below 0.8, and for fossil-fuel production around 0.9 to 0.95.

For technologies in early stages of development, other factors may also contribute to technology progress, such as relatively high investment in research and development (Wene, 2000). In TIMER, the existence of a single global learning curve is postulated. Regions are then assumed to pool knowledge and 'learn' together or, depending on the scenario assumptions, are partly excluded from this pool. In the last case, only the smaller cumulated production in the region would drive the learning process and costs would decline at a slower rate.

The production costs for bioenergy are represented by the costs of feedstock and conversion. Feedstock costs increase with actual production as a result of depletion, while conversion costs decrease with cumulative production as a result of 'learning by doing'. Feedstock costs include the costs of land, labour and capital, while conversion costs include capital, O&M and energy use in this process. For both steps, the associated greenhouse gas emissions (related to deforestation, N_2O from fertilisers, energy) are estimated (see Section 5.2, Emissions), and are subject to carbon tax, where relevant.

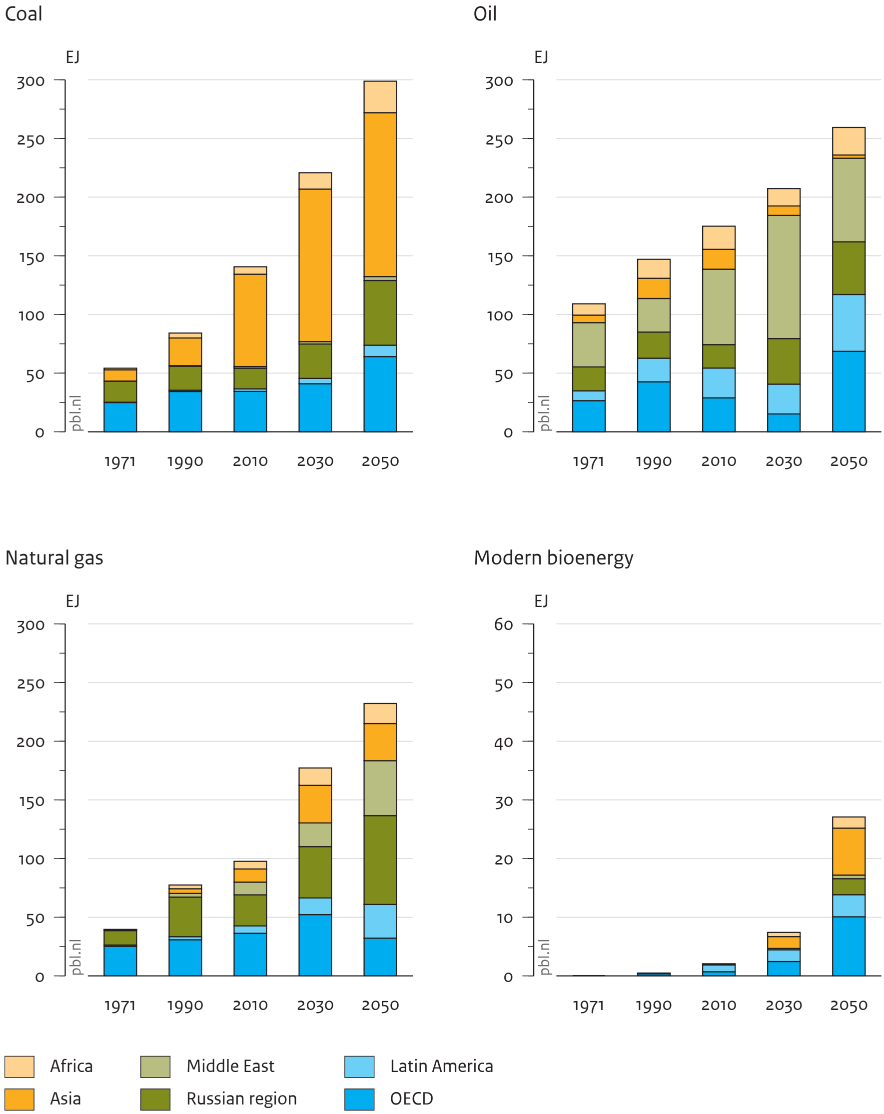
Other renewable energy
Potential supply of renewable energy (wind, solar and bioenergy) is estimated generically as follows (Hoogwijk, 2004; De Vries et al., 2007):

1. Physical and geographical data for the regions considered are collected on a 0.5x0.5 degree grid. The characteristics of wind speed, insulation and monthly variation are taken from the digital database constructed by the Climate Research Unit (New et al., 1997).
2. The model assesses the part of the grid cell that can be used for energy production, given its physical–geographic (terrain, habitation) and socio-geographical (location, acceptability) characteristics. This leads to an estimate of the geographical potential. Several of these factors are scenario-dependent. The geographical potential for biomass production from energy crops is estimated using suitability/availability factors taking account of competing land-use options and the harvested rain-fed yield of energy crops.
3. Next, we assume that only part of the geographical potential can be used due to limited conversion efficiency and maximum power density, This result of accounting for these conversion efficiencies is referred to as the technical potential.
4. The final step is to relate the technical potential to on-site production costs. Information at grid level is sorted and used as supply cost curves to reflect the assumption that the lowest cost locations are exploited first. Supply cost curves are used dynamically and change over time as a result of the learning effect.

3. Policy issues

Baseline developments
Under the baseline scenario, demand for energy increases rapidly, and as a consequence, supply is projected to increase in the coming decades for all energy supply options. Under the baseline scenario, energy demand is mostly met by fossil fuels but shifts in dominant energy carriers and main supply regions are also projected (Figure 4.1.3.2). For coal, the model indicates continuous rise in production, mostly in the regions already producing the largest shares of global output. For oil, the model also shows continuous increase in production in the coming decades, with an increase in unconventional sources, mainly from Canada and South America.

Figure 4.1.3.2
Energy production per region under a baseline scenario



Source: PBL 2012

Over time the share of most important energy producers for different forms of energy changes. This has implications for energy security.

Natural gas is expected to rise faster in production because it is presumed to be more abundant and increasingly more cost competitive, with unconventional sources becoming increasingly more important. Main gas producers are the United States, the former Soviet Union and increasingly the Middle East.

Production of modern types of bioenergy is constantly increasing and in different parts of the world. For solar and wind, the most rapid increase so far has been in western Europe, the United States and China. In the future, parts of South America and India are expected to produce large amounts of renewable energy. Nuclear power is expected to remain roughly at the same level, and uranium production to remain more or less stable and rather evenly distributed across world regions. Finally, hydropower capacity shows a modest increase under the baseline scenario.

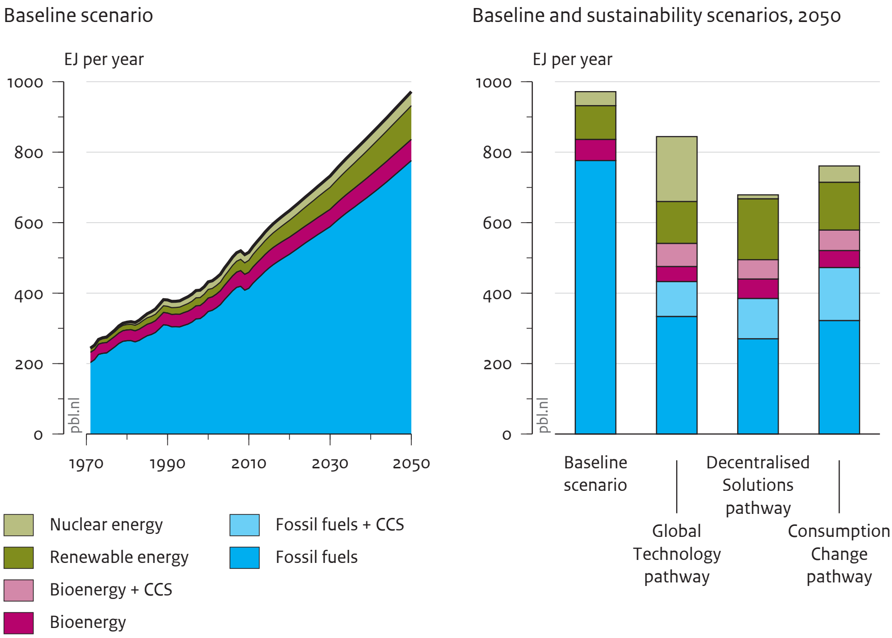
Policy interventions

The model can simulate various policies on the supply side:

- Carbon tax. As discussed, a carbon tax can lead to significant changes in the demand for fuels and therefore, also supply.
- Restrictions on fuel trade. As part of energy security policies, fuel trade between different regions can be blocked.
- Sustainability criteria for bioenergy production may restrict production in water-scarce areas.
- Production targets are mostly set to force technologies through a learning curve.

The influence of stringent climate policy on production of primary energy resources is shown in Figure 4.1.3.3. Climate policy leads to a major shift from a system mostly based on fossil fuels to an increase in the use of nuclear power, renewable energy, bioenergy and CCS technology, with a correspondingly lower reliance on fossil fuels. The choice of these alternative options depends on assumptions made in the model, as shown in the scenarios in the study Roads from Rio+20 (PBL, 2012). Three pathways based on different initial assumptions emphasise different combinations of primary energy carriers, each time within a stringent emission constraint.

Figure 4.1.3.3
Global primary energy supply



Source: PBL 2012

Policies to meet the 2 ° Celsius target will lead to significant changes in the energy supply mix.

4. Data, uncertainties and limitation

Data
Main data for the supply side of TIMER are the size of the resources available at different production costs (Table 4.1.3.2).

Table 4.1.3.2
Main data sources for the TIMER energy supply module

Data input	Sources
Fossil-fuel resources and costs	(Mulders et al., 2006). Costs from various sources
Nuclear fuel data (uranium and thorium)	World Energy Council (WEC, 2010)
Bioenergy potential and costs	PBL calculations (Van Vuuren et al., 2009; Van Vuuren et al., 2010)
Solar and wind potential	PBL calculations (Hoogwijk, 2004)
CCS potential	Based on (Hendriks et al., 2004a; IPCC, 2005)

Uncertainties
One of the main uncertainties with respect to long-term supply is the size of the resource estimates at various production costs. Estimates of energy resources vary significantly, especially non-conventional resource estimates for oil and natural gas. Equally important uncertainties are the nature and rate of technological advances, and the design and implementation of energy policies in different regions.

Various PBL publications have analysed the sensitivity of the model to supply uncertainties. The Monte Carlo uncertainty analysis of various scenarios (Van Vuuren et al., 2008) identified model parameters as important determinants of the future supply such as oil and natural gas resources and renewable energy learning rates. Some of these factors were only important for a subset of scenario output. For instance, size of oil resources was found to directly influence future oil production, but had limited impact on future CO_2 emissions. The main reason is that oil production in the medium-term is constrained by competition from other fossil fuels and bioenergy. The results were also shown to be scenario dependent. Fossil fuel related uncertainties were more important in a scenario that resulted in a high rather than low fossil-fuel demand.

Limitations
The general limitations of TIMER also apply to energy supply modules with a few specific limitations. As a global model, TIMER specifies resource availability in 26 global regions. However, to some degree this does not take into account the underlying geographical dimensions of individual countries and specific areas. For fossil fuels, this issue leads to heterogeneity within a region (e.g., due to different tax systems), but is more important for renewable energy. A key factor can be transport from one area to another, and calculations require the use of other models.

Another main limitation concerns the focus on production costs in describing energy markets. Although long-term developments may be expected to be driven by long-term supply costs over the last few decades, issues related to capacity constraints and market formation over longer time periods have lead to fossil fuels prices that differ from production costs.

5. Key publications

De Vries BJM, Van Vuuren DP and Hoogwijk MM. (2007). Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. *Energy Policy* 35(4), pp. 2590–2610.
Van Vuuren DP, De Vries B, Beusen A and Heuberger PSC. (2008). Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. *Global Environmental Change* 18(4), pp. 635–654.
Van Vuuren DP, van Vliet J and Stehfest E. (2009). Future bio-energy potential under various natural constraints. *Energy Policy* 37(11), pp. 4220–4230.

6. Input/Output Table

Table 4.1.3.1
Input in and output from the energy supply module of TIMER

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Energy resources	Volume of energy resource per carrier, region and supply cost class (determines depletion dynamics).	3
Learning rate	Determines the rate of technology development in learning equations.	3
Technology development of energy supply	Learning curves and exogenous learning that determine technology development.	3
Trade restriction	Trade tariffs and barriers limiting trade in energy carriers (in energy submodel).	3
Demand for primary energy	Total demand for energy production. Sum of final energy demand and energy inputs into energy conversion processes.	4.1.2
Potential bioenergy yield - grid	Potential yields of bioenergy crops.	6.2
Land supply for bioenergy - grid	Land available for sustainable bioenergy production (abandoned agricultural land and non-forested land).	5.1
External datasets		
Initial production costs	The costs of energy conversion technologies at the start of the simulation.	Various sources
Output	**Description**	**Use (section)**
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	5.2
Bioenergy production	Total bioenergy production.	4.2.3
Primary energy price	The price of primary energy carriers based on production costs.	4.1.1, 4.1.2
Marginal abatement cost	Cost of an additional unit of pollution abated (CO_2eq). A marginal abatement cost curve (MAC curve) is a set of options available to an economy to reduce pollution, ranked from the lowest to highest additional costs.	8.1
Carbon storage price	The costs of capturing and storing CO_2, affecting the use of CCS technology.	4.1.2
Energy security indicators	Indicators on the status of energy security, such as energy self-sufficiency.	Final output
Total primary energy supply	Total primary energy supply.	Final output

4.2 Agriculture and land use

4.2.1 Agricultural economy

Elke Stehfest, Hans van Meijl, Anne Gerdien Prins, Andrzej Tabeau

Key policy issues

- What is the area of cropland and grassland required to support future food demand?
- What are the policy options to reduce agricultural land use and to safeguard global biodiversity, while ensuring food security?
- How can the implications of biofuels for land use and greenhouse gases be managed sustainably?

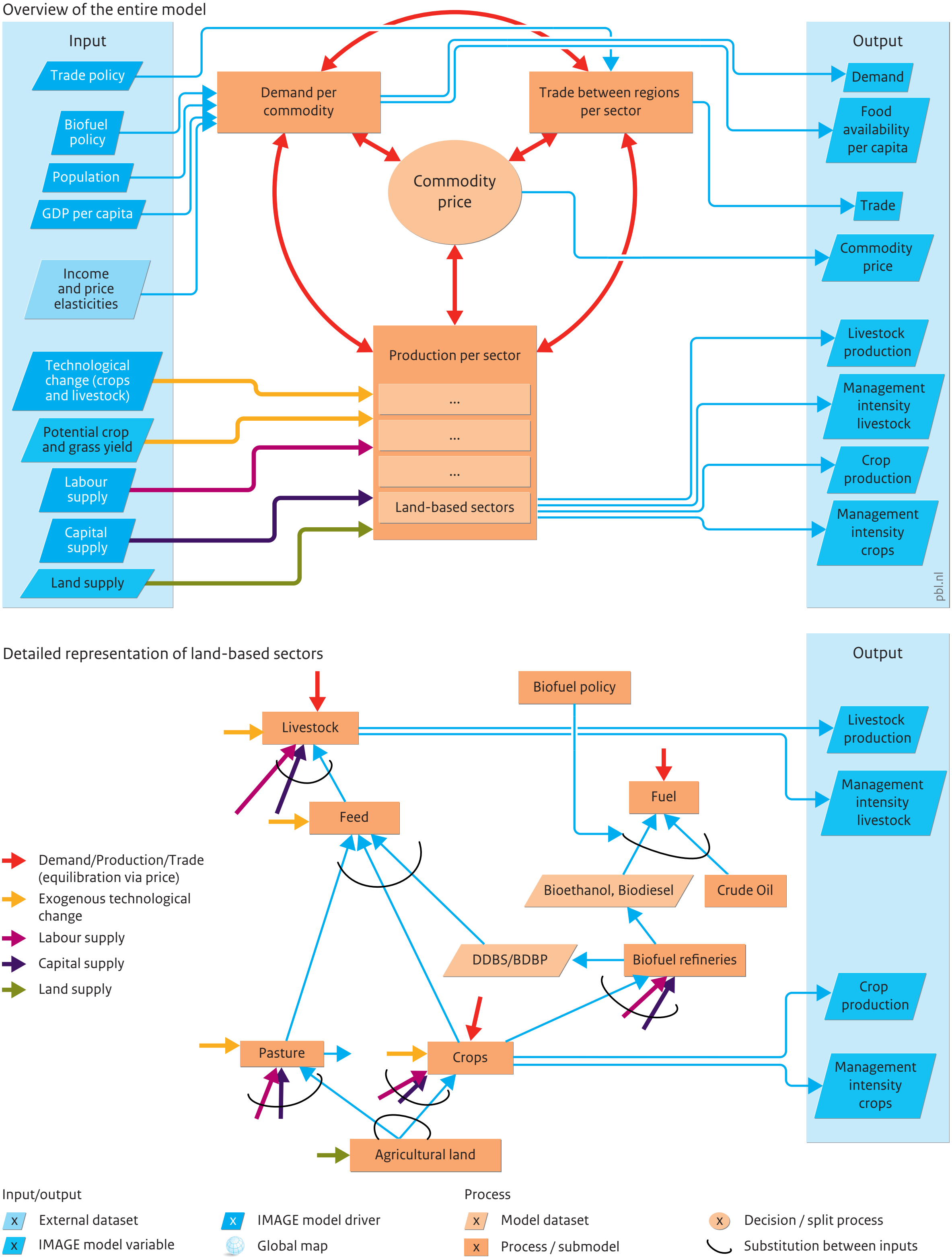
1. Introduction

As a result of the growing world population and higher per capita consumption, production of food, feed, fibres and other products, such as bioenergy and timber, will need to increase rapidly in the coming decades. Even with the expected improvements in agricultural yields and efficiency, there will be increasing demand for more agricultural land. However, expansion of agricultural land will lead to deforestation and increases in greenhouse gas emissions, loss of biodiversity and ecosystem services, and nutrient imbalances. To reduce these environmental impacts, a further increase in agricultural yields is needed, together with other options such as reduced food losses, dietary changes, improved livestock systems, and better nutrient management.

In the IMAGE framework, future development of the agricultural economy can be calculated using the agro-economic model MAGNET (formerly LEITAP; Woltjer et al. (2011); Woltjer et al. (2014)). MAGNET is a computable general equilibrium (CGE) model that is connected via a soft link to the core model of IMAGE. Demographic changes and rising incomes are the primary driving factors of the MAGNET model, and lead to increasing and changing demand for all commodities including agricultural commodities. In response to changing demand, agricultural production is increasing, and the model also takes into account changing prices of production factors, resource availability and technological progress. In MAGNET, agricultural production supplies domestic markets, and other countries and regions are supplied via international trade, depending on historical trade balances, competitiveness (relative price developments), transport costs and trade policies. MAGNET uses information from IMAGE on land availability and suitability, and on changes in crop yields due to climate change and agricultural expansion on inhomogeneous land areas. The results from MAGNET on

Figure 4.2.1.1

MAGNET, the agro-economic model in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.2.1.1).

production and endogenous yield (management factor) are used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity, and climate.

Although MAGNET is the standard agro-economic model used with IMAGE, other models can be linked to IMAGE as well. For example, the IMPACT model was used with IMAGE in the Millennium Ecosystem Assessment (Carpenter et al., 2006), and in a PBL study on protein supply, both the MAGNET and the IMPACT model were used to study the same set of scenarios. This allowed a systematic comparison between IMPACT and MAGNET (Stehfest et al., 2013).

In IMAGE, demand for forest products can be derived from several sources, the most simplest being via a relationship with GDP or preferably, from specific forest demand models, such as EFI-GTM (Kallio et al., 2004). In the future, competition between forestry and other land uses can be included using the forestry module in MAGNET. Other land-use changes, such as infrastructure expansion, which do not require interregional links, are described in the land-use allocation model (Section 4.1.3).

2. Model description

The MAGNET model (Woltjer et al., 2011; Woltjer et al., 2014) is based on the standard GTAP model (Hertel, 1997), which is a multi-regional, static, applied computable general equilibrium (CGE) model based on neoclassical microeconomic theory. Although the model covers the entire economy, there is a special focus on agricultural sectors (Figure 4.2.1.1). It is a further development of GTAP regarding land use, household consumption, livestock, food, feed and energy crop production, and emission reduction from deforestation.

Demand and supply: Household demand for agricultural products is calculated based on changes in income, income elasticities, preference shift, price elasticities, cross-price elasticities, and the commodity prices arising from changes in the supply side. Demand and supply are balanced via prices to reach equilibrium. Income elasticities for agricultural commodities are consistent with FAO estimates (Britz, 2003), and dynamically depend on purchasing power parity corrected GDP per capita. The supply of all commodities is modelled by an input–output structure that explicitly links the production of goods and services for final consumption via different processing stages back to primary products (crops and livestock products) and resources. At each production level, input of labour, capital, and intermediate input or resources (e.g., land) can be substituted for one another. For example, labour, capital and land are input factors in crop production, and substitution of these production factors is driven by changes in their relative prices. If the price of one input factor increases, it is substituted by other factors, following the price elasticity of substitution.

Regional aggregation and trade: MAGNET is flexible in its regional aggregation (129 regions). In linking with IMAGE, MAGNET distinguishes individual European countries and 22 large world regions, closely matching the regions in IMAGE (Figure 1.3, IMAGE regions). Similar to most other CGE models, MAGNET assumes that products traded internationally are differentiated according to country of origin. Thus, domestic and foreign products are not identical, but are imperfect substitutes (Armington assumption; Armington, 1969).

Land use: In addition to the standard GTAP model, MAGNET includes a dynamic land-supply function (Van Meijl et al., 2006) that accounts for the availability and suitability of land for agricultural use, based on information from IMAGE (see below). A nested land-use structure accounts for the differences in substitutability of the various types of land use (Huang et al., 2004; Van Meijl et al., 2006). In addition, MAGNET includes international and EU agricultural policies, such as production quota and export/import tariffs (Helming et al., 2010).

Biofuel crops: MAGNET includes ethanol and biodiesel as first-generation biofuels made from wheat, sugar cane, maize, and oilseeds (Banse et al., 2008) and the use of by-products (DDGS, oilcakes) from biofuel production in the livestock sector.

Livestock: MAGNET distinguishes the livestock commodities of beef and other ruminant meats, dairy cattle (grass- and crop-fed), and a category of other animals (e.g., chickens and pigs) that are primarily crop fed. Modelling the livestock sector includes different feedstuffs, such as feed crops, co-products from biofuels (oil cakes from rapeseed-based biofuel, or distillers grain from wheat-based biofuels), and grass (Woltjer, 2011). Grass may be substituted by feed from crops for ruminants.

Land supply: In MAGNET, land supply is calculated using a land-supply curve that relates the area in use for agriculture to the land price. Total land supply includes all land that is potentially available for agriculture, where crop production is possible under soil and climatic conditions, and where no other restrictions apply such as urban or protected area designations (see also Section 4.2.3). In the IMAGE model, total land supply for each region is obtained from potential crop productivity and land availability on a resolution of 5x5 arcminutes. The supply curve depends on total land supply, current agricultural area, current land price, and estimated price elasticity of land supply in the starting year. Recently, the earlier land supply curve (Eickhout et al., 2009) has been updated with a more detailed assessment of land resources and total land supply in IMAGE (Mandryk et al., in prep.), and with literature data on current price elasticities. Regions differ with regard to the proportion of land in use, and with regard to change in land prices in relation to changes in agricultural land use. In regions where most of the area suitable for agriculture is in use, the price elasticity of land supply is small, with little expansion occurring at high price changes. In contrast, in regions with a large reserve of suitable agricultural land, such as Sub-Saharan Africa and some regions in

South America, the price elasticity of land supply is larger, with expansion of agricultural land occurring at smaller price changes.

Reduced land availability: By restricting land supply in IMAGE and MAGNET, the models can assess scenarios with additional protected areas, or reduced emissions from deforestation and forest degradation (REDD). These areas are excluded from the land supply curve in MAGNET, leading to lower elasticities, less land-use change and higher prices, and are also excluded from the allocation of agricultural land in IMAGE (Overmars et al., accepted).

Intensification of crop and pasture production: Crop and pasture yields in MAGNET may change as a result of the following four processes:
(i) autonomous technological change (external scenario assumption);
(ii) intensification due to the substitution of production factors (endogenous);
(iii) climate change (from IMAGE);
(iv) change in agricultural area affecting crop yields (such as, decreasing average yields due to expansion into less suitable regions; from IMAGE).

Biophysical yield effects due to climate and area changes are calculated by the IMAGE crop model (Section 6.2) and communicated to MAGNET. Likewise, also the potential yields and thus the yield gap can be assessed with the crop model in IMAGE. External assumptions on autonomous technological changes are mostly based on FAO projections (Alexandratos and Bruinsma, 2012), which describe, per region and commodity, the assumed future changes in yields for a wide range of crop types. In MAGNET, the biophysical yield changes are combined with the autonomous technological change to give the total exogenous yield change. In addition, during the simulation period, MAGNET calculates an endogenous intensification as a result of price-driven substitution between labour, land and capital. In IMAGE, regional yield changes due to autonomous technological change and endogenous intensification according to MAGNET are used in the spatially explicit allocation of land use (Section 4.2.3).

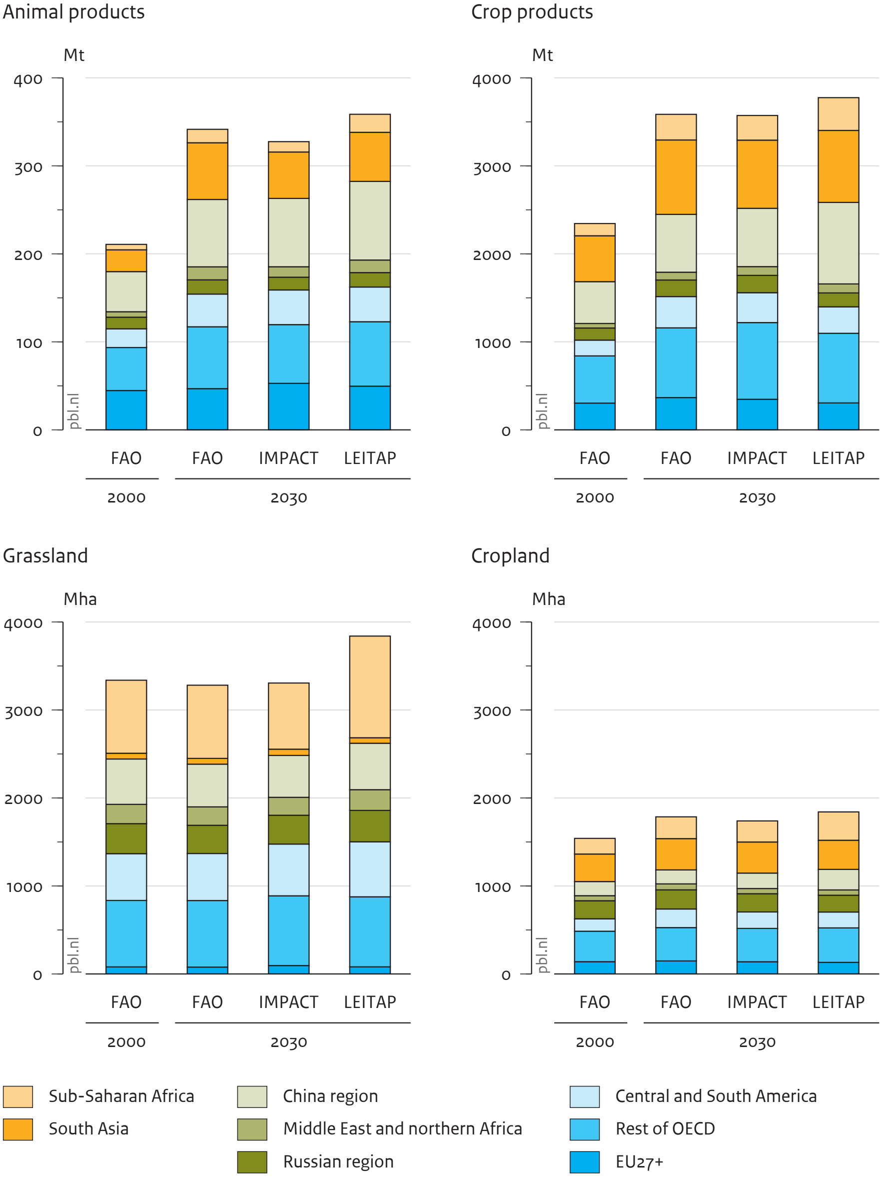
3. Policy issues

Baseline developments

In a baseline scenario, agricultural crop and livestock production increases rapidly driven by population increase and dietary changes. This is also the case in baseline scenarios shown in Figure 4.2.1.2 that are based on FAO projections, and on MAGNET and IMPACT calculations (Stehfest et al. 2013). As a consequence of production increases, the total area of cropland and pasture is projected to increase, although this is less certain. Depending on scenario and region, some baseline scenarios may also show decreasing land areas, certainly after 2030 when the population starts to decline in several regions.

Figure 4.2.1.2

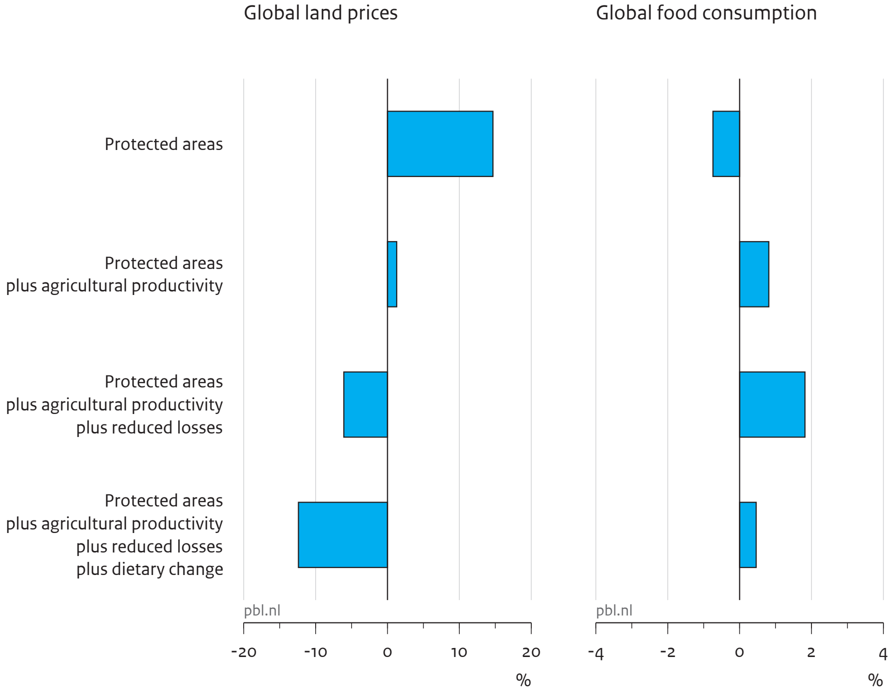
Global agricultural production and areas per region



Source: Stehfest et al. 2013

Agricultural production increases strongly between 2000 and 2030, according to an implementation of FAO projections (Bruinsma, 2003) in IMAGE, and according to IMPACT and MAGNET (formerly LEITAP) projections (Stehfest et al., 2013). Changes in agricultural areas differ across models.

Figure 4.2.1.3
Change in land prices and food consumption under stepwise introduction of biodiversity options, compared to baseline scenario, 2030



Source: PBL 2010

Some biodiversity-preserving options increase the pressure on land, leading to increasing prices and reduced food consumption, while others reduce the pressure on land, leading to lower prices and increased food consumption (adopted from PBL (2010)).

Policy interventions

Numerous policy interventions can be studied with the linked IMAGE-MAGNET and IMAGE-IMPACT framework:

- Biofuel policies: Partly as an autonomous process under high oil prices but mainly driven by biofuel policies, the proportion of biofuels (so far, only first generation) in the transport sector is projected to increase (Banse et al., 2008). The model can be used to estimate direct and indirect land-use change and associated emissions.
- REDD policies: Forest protection leads to a reduction in CO_2 emissions from land-use change. The related opportunity costs can be used to estimate cost curves for the emission abatement that results from REDD policies (Overmars et al., accepted).
- Agricultural and trade policies can be assessed for their effects on land use, greenhouse gas emissions and biodiversity (Verburg et al., 2009).

- Measures to reduce biodiversity loss by increasing protected areas, increasing agricultural productivity, dietary changes, and reducing waste (PBL, 2010). Several biodiversity options, in a stepwise introduction, affect land and commodity prices as well as land-use change (Figure 4.2.1.3).
- Consumption changes, dietary preferences, and their effect on global land use, prices and emissions can be studied (PBL, 2011; Stehfest et al., 2013)
- Changes in crop and livestock production systems, such as more efficient production methods, or organic farming can be assessed (PBL, 2011; Westhoek et al., in prep.).

4. Data, uncertainty and limitations

Data

The MAGNET model uses the GTAP8 database for sectoral input–output tables and bilateral trade in the reference year 2007 (Narayanan et al., 2012). The model applies all GTAP sectors for agriculture but industrial and service sectors are aggregated into a few groups of sectors. The regional representation of GTAP is aggregated to match the IMAGE regions outside Europe, but data are kept at country level. For the start year, agricultural land use for both arable land and permanent grassland is based on FAO statistics. In addition, the model also uses a large number of essential coefficients, such as Armington trade elasticities, consumption function parameters, substitution elasticities for all production nests, CET elasticities for land-use transformations, and elasticities in the land-supply curve. Some parameters are based on econometric research or economic literature, while others are no more than 'best guesses' (Woltjer et al., 2011). The autonomous technological yield change is often based on FAO projections in both MAGNET and IMAGE (Alexandratos and Bruinsma, 2012).

Uncertainties

To date, no systematic uncertainty analyses have been carried out for models on the agricultural economy, including the MAGNET model. However, a comparison of the LEITAP (now MAGNET) and IMPACT models has revealed large differences in model results, even more in policy scenarios than in baseline projections (Stehfest et al., 2013).

A recent model comparison within AgMIP included ten global agro-economic models using harmonised scenario drivers (Nelson et al., 2014; Von Lampe et al., 2014). Results indicate that MAGNET is in the upper range of other models, in terms of future land-use expansion. This is probably due to the relatively large land supply in MAGNET, which allows further expansion of agricultural land, particularly in North and South America, and Africa. In contrast, several other models do not explicitly consider agricultural land expansion, but only allow interchanges between, for example, arable land and grassland. In addition to land supply, the most relevant uncertainties in MAGNET are autonomous technological change, relative contribution of intensification or expansion to total production growth, retaining current trade patterns in long-term scenarios, and dynamics in the livestock sector, especially with respect to pasture area and grassland intensification (Stehfest et al., 2013), and long-term dietary preferences. The empirical basis for many of these parameters in MAGNET and all other agro-economic models needs to be improved (Hertel, 2011).

Limitations

The MAGNET model provides a complete and internally consistent view of the world economy, covering all economic sectors, and a dynamic modelling of all primary and intermediate production and demand. However, a little known limitation, is the uncertainties in constructing the GTAP/MAGNET database because many ad hoc assumptions need to be made to fill the database, for instance, allocating value added across inputs.

Furthermore, volumes in the model are not expressed in physical terms but in monetary values. Likewise, all substitutions in the model are based on monetary values. As a consequence, there is no guarantee that changes in composition are consistent with the physical requirements, such as in livestock feed. Thus, a closer link to physical units is needed (Woltjer, 2011).

Because of the highly aggregated and general character of MAGNET, most elasticities are kept constant over time. Some improvements have been introduced in the consumption function, by making the income elasticities dependent on income levels. Armington elasticities are also constant, and thus small trade flows in the starting year only increase very slowly in future years.

Although some limitations can be reduced by adding physical units and improving the empirical basis for the main elasticities, many simplifications in agro-economic models will remain. MAGNET provides a consistent system to assess economy-wide effects of policy measures on land use, income, welfare and production, and supports policy-makers and scientists in gaining insights into the complex interlinkages in the agricultural system. Nevertheless, simplifications and uncertainties that result from such a broad coverage need to be kept in mind when interpreting results.

5. Key publications

Woltjer GB, Kuiper M, Kavallari A, van Meijl H, Powell J, Rutten M, Shutes L and Tabeau A (2014). The Magnet Model – Module description. LEI, part of Wageningen University and Research Centre, The Hague.

Von Lampe M, Willenbockel D, Calvin K, Fujimori S, Hasegawa T, Havlik P, Kyle P, Lotze-Campen H, Mason d'Croz D, Nelson G, Sands R, Schmitz C, Tabeau A, Valin H, van der Mensbrugghe D and van Meijl H. (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics, Special Issue on Global Model Intercomparison (forthcoming)* 45(1), pp. 1574–0862, DOI: 10.1111/agec.12086.

Stehfest E, Berg M, Woltjer G, Msangi S and Westhoek H. (2013). Options to reduce the environmental effects of livestock production - Comparison of two economic models. *Agricultural Systems* 114, pp. 38–53.

6. Input/Output Table

Table 4.2.1.1
Input in and output from the agro-economic model MAGNET

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	3
Population	Number of people per region.	3
Capital supply	Capital available to replace depreciated stock and expand the stock to support economic growth.	3
Labour supply	Effective supply of labour input to support economic activities, taking into account the participation rate of age cohorts.	3
Biofuel policy	Policies to foster the use of biofuels in transport, such as financial incentives and biofuel mandates and obligations.	3
Trade policy	Assumed changes in market and non-market instruments that influence trade flows.	3
Technological change (crops and livestocks)	Increase in productivity in crop and grass production (yield/ha) and livestock production (carcass weight, offtake rate, feed).	3
Land supply	Available land for agriculture, per grid or region, depending on suitability for crops, and excluding unsuitable areas such as steep slopes, wetlands and protected areas.	5.1

Potential crop and grass yield - grid	Potential crop and grass yield, changing with time due to climate change and possibly soil degradation.	6.2
External datasets		
Income and price elasticities	Assumptions on income and price elasticities of demand, substitution elasticities, and many other elasticities.	GTAP database and other assumptions
Output	**Description**	**Use (section)**
Crop production	Regional production per crop.	4.2.3, 7.6
Management intensity crops	Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions - current practice and technological change in agriculture - and is endogenously adapted in the agro-economic model.	4.2.3, 5.1, 6.2, 7.2
Livestock production	Production of livestock products (dairy, beef, sheep and goats, pigs, poultry).	4.2.4, 7.6
Management intensity livestock	Management intensity of livestock, based current practice and technological change in livestock sectors, describing carcass weight and feed requirements of livestock.	4.2.4, 5.1, 7.2
Food availability per capita	Food availability per capita.	7.7
Demand (all commodities)	Demand per sector including various crop and livestock sectors.	Final output
Trade (all commodities)	Bilateral trade between regions per sector, including various crop and livestock sectors.	Final output
Commodity price	Commodity price per sector, including various crop and livestock sectors.	Final output

4.2.2 Forest management

Jelle van Minnen, Liesbeth de Waal, Coen Wagner, Mark van Oorschot, Elke Stehfest

Key policy issues:

- How can management influence forest capacity to meet future demand for wood and other ecosystem services?
- What are the implications of forest management for pristine and managed forest areas, and on carbon stocks and fluxes of relevance for climate policy?
- What are the prospects for more sustainable forest management and the role of production in dedicated forest plantations?

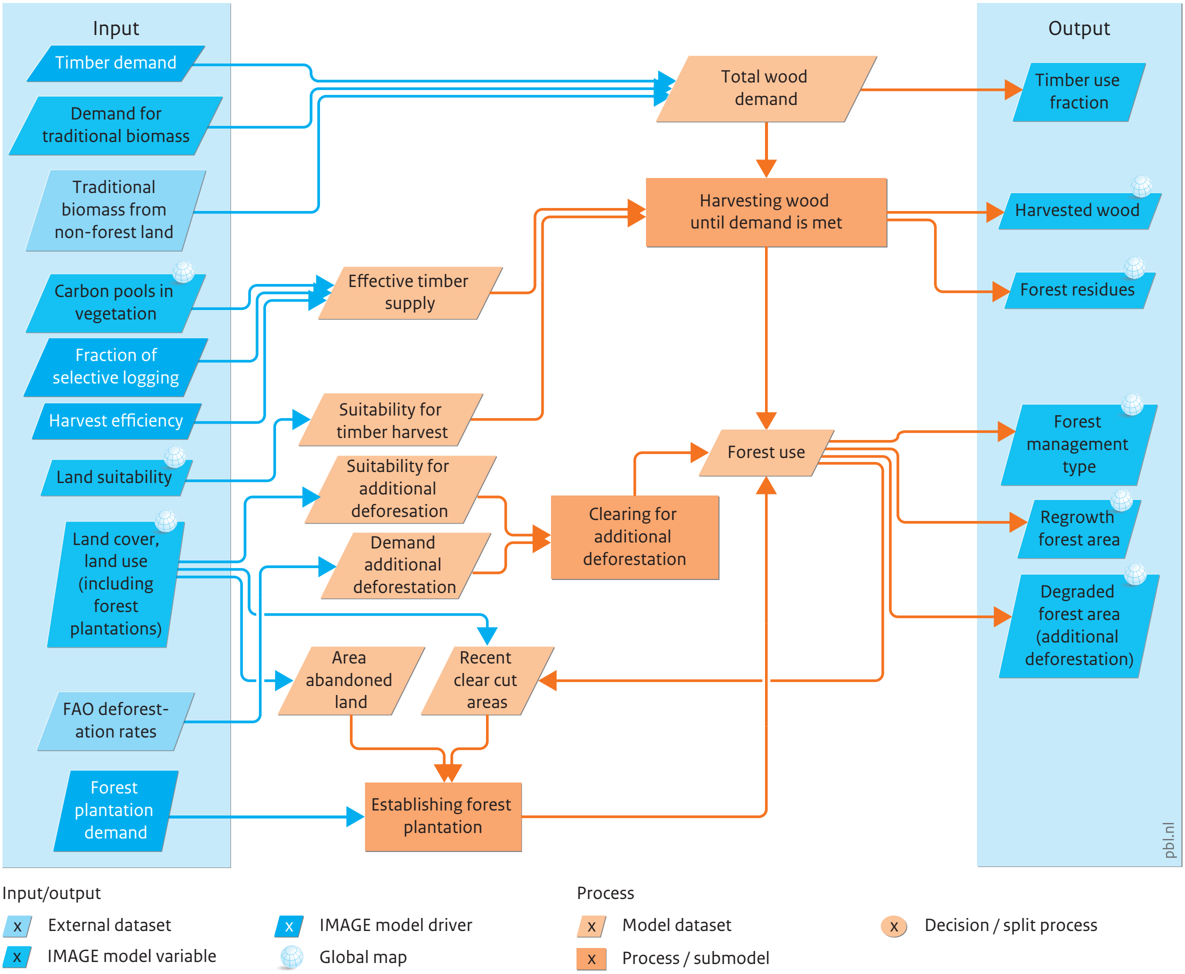
1. Introduction

The global forest area and wooded land area have been estimated for 2010 at just over 40 and 11 million km^2, respectively (FAO, 2010). Forest resources are used for a multitude of purposes, including timber, fuel, food, water and other forest-related goods and services. In addition, (semi-) natural forests are home to many highly valued species of interest for nature conservation and biodiversity.

The total global forest area is continuing to decline at difference rates in different world regions. Although the rate of global deforestation has decreased in the last decade, deforestation is still occurring on a significant scale in large parts of Latin America, Africa and Southeastern Asia. At the same time, net forest area is expanding in some regions, such as in Europe and China (FAO, 2010). Sustainable management of global forest resources may contribute to preserving forests, slowing down or reversing degradation processes, and conserving forest biodiversity and carbon stocks (FAO, 2010).

Several types of forest management systems are employed in meeting the worldwide demand for timber, paper, fibreboard, traditional or modern bioenergy and other products. Management practices depend on forest type, conservation policies and regulation, economics, and other, often local, factors. Practices differ with respect to timber volume harvested per area, rotation cycle, and carbon content and state of biodiversity of the forested areas.

Figure 4.2.2.1.
Forest management module in IMAGE 3.0



Source: PBL 2014

The option of forest plantations in IMAGE and LPJmL is still under development, and expected to be available soon. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.2.2.1).

Modelling of forests and forest management is an integral part of the IMAGE 3.0 framework, with a simulated forest area in 2010 at about 46 million km², somewhat larger than observed by FAO as this area includes fractions of other wooded land (see Section 6.1). To manage these forests, three forest management systems are defined in IMAGE 3.0 in a simplification of the range of management systems implemented worldwide (Carle and Holmgren, 2008; Arets et al., 2011). The first forest management system is clear cutting or clear felling, in which all trees in an area are cut down followed by natural or 'assisted' regrowth, as widely applied in temperate regions. The second forest management system is selective logging, in which only trees of the highest economic value are felled, commonly used in tropical forests with a high heterogeneity of tree species. An ecological variant of selective logging is reduced impact logging (RIL) directed to reducing harvest damage, stimulating regrowth and maintaining bio-diversity levels (Putz et al., 2012). The third forest management system considered in IMAGE 3.0 is forest plantations, such as hardwood tree plantations in the tropics, and poplar plantations in temperate regions. Selected tree species, either endemic or exotic to the area, are planted and managed intensively, for example through pest control, irrigation and fertiliser use, to maximise production. Forest plantations generally have a high productivity level (FAO, 2006). By producing more wood products on less land, plantations may contribute to more sustainable forest management by reducing pressure on natural forests (Carle and Holmgren, 2008; Alkemade et al., 2009). However, the ecological value of biodiversity in many forest plantations is relatively low (Hartmann et al., 2010).

2. Model description

The forest management module describes regional timber demand and the production of timber in the three different management systems clear felling, selective felling and forest plantations. Deforestation rates reported by FAO are used to calibrate deforestation rates in IMAGE, using a so called additional deforestion (Figure 4.2.2.1).

Timber demand

In IMAGE 3.0, the driver for forest harvest is timber demand per region. Timber demand is the sum of domestic and/or regional demand and timber claims by other regions (export/trade). Production and trade assumptions for saw logs and paper/pulp wood are adopted from external models, such as EFI-GTM (Kallio et al., 2004), and domestic demand for fuelwood is based on the TIMER model (See Section 4.1).

Part of the global energy supply is met by fuelwood and charcoal, in particular in less developed world regions. Not all wood involved is produced from formal forestry activities, as it is also collected from non-forest areas, for example from thinning orchards and along roadsides (FAO, 2001a; FAO, 2008). As few reliable data are available on fuelwood production, own assumptions have been made in IMAGE. While fuelwood production in industrialized regions is dominated by large-scale, commercial operations, in transitional and developing regions smaller proportions of fuelwood volumes are assumed to come from forestry operations: 50% and 32% respectively.

Timber supply & production in forests

In IMAGE, felling in each region follows a stepwise procedure until timber demand is met, attributed to the three aforementioned management systems. The proportion for each management system is derived from forest inventories for different world regions (Arets et al., 2011) and used as model input (Figure 4.2.2.1). Firstly, timber from forest plantations at the end of their rotation cycle is harvested. Secondly, trees from natural forests are harvested, applying clear felling and/or selective felling. In all management systems, trees can only be harvested when the rotation cycle of forest regrowth has been completed.

Selective logging: Under selective felling, only a – regional and time specific – fraction of the trees is logged and the other trees remain in the forest. After logging, a fraction of the harvested wood is removed from the forest to fulfil the demand. Biomass left behind in the forest represents losses/residues during tree harvesting (from tree damage and unusable tree parts) or left in the forest because of environmental concerns (biodiversity and nutrient supply). The fraction take-away is derived from literature, defined for industrial roundwood (see Arets et al., 2011). It is further adjusted to account for the demand for wood fuel, for which it equals unity.

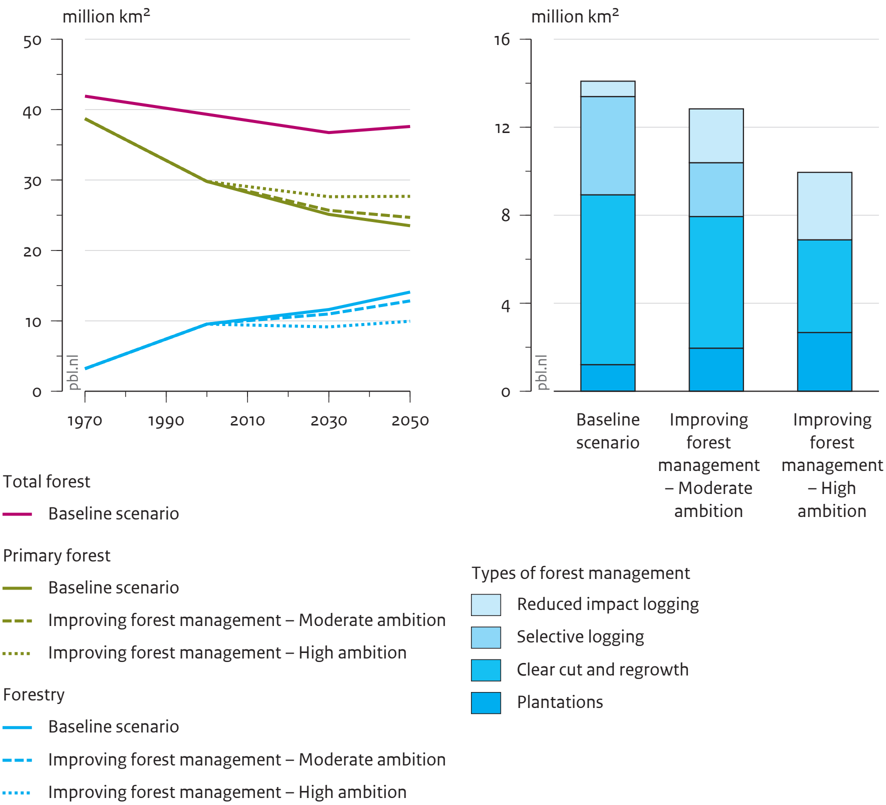
Forest plantations: Forest plantations are established for efficient, commercially viable wood production. Their regional establishment in IMAGE 3.0 is scenario driven (see also Table 4.2.2.1), based on FAO. The expectation is that increasingly more wood will be produced in plantations because sustainability criteria may limit harvest from natural forests (Brown, 2000; Carle and Holmgren, 2008; FAO, 2012b). The development of forest plantations in IMAGE and LPJmL is still under development, but expected to be available soon. Forest plantations are assumed to be established firstly on abandoned agricultural land. When sufficient abandoned land is not available, forest plantations are established on cleared forest areas. When a forest plantation has been established, the land cannot be used for other purposes or converted to natural vegetation until the tree rotation cycle has been completed.

Additional deforestation

Globally, conversion to agricultural land is the major driver of forest clearing, and timber harvest does not result in deforestation, if natural vegetation is regrowing. But there are other causes of deforestation not related to food demand and timber production, such as urbanisation, mining and illegal logging. These activities contribute to loss of forest area, increased degradation risks and a decline in the supply of forest services. To be consistent with the total deforestation rates per world region reported by the FAO (2010), IMAGE 3.0 introduces a category 'additional deforestation'. IMAGE assumes no recovery of natural vegetation in these areas, and no agricultural activities.

Figure 4.2.2.2
Forests and forestry

Primary forests and forestry | Forestry, 2050



Source: PBL 2010

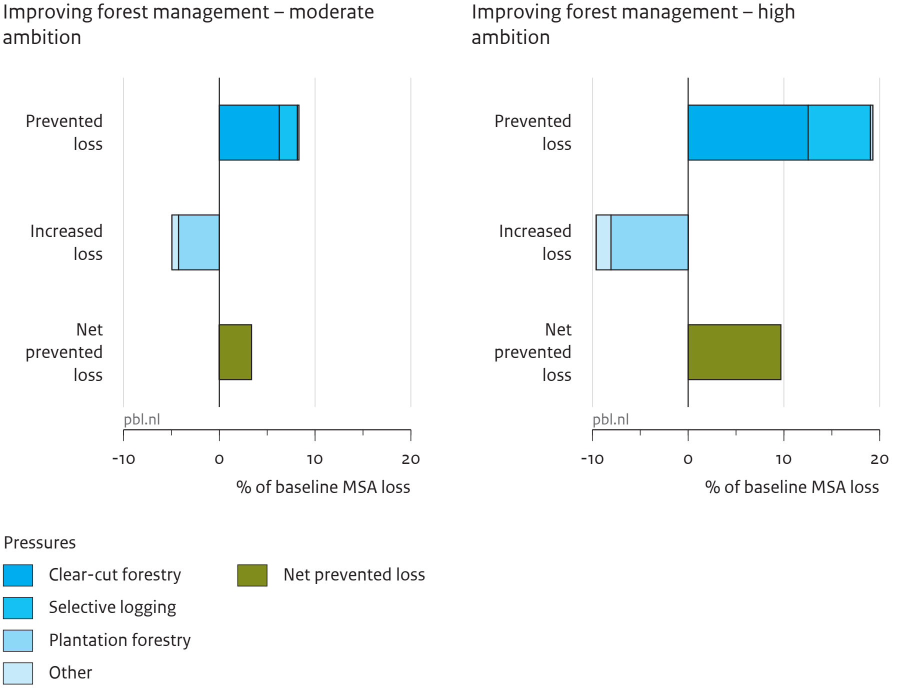
Areas of managed forest are projected to increase in the coming decades; improved forest management, especially forest plantations, could limit the area required for wood production.

3. Policy issues

Baseline developments

In most baseline scenarios, areas of forest management increase. The IMAGE forest management model was used in the scenario study 'Rethinking global biodiversity strategies' on future biodiversity developments (PBL, 2010). The study projects that, in the absence of additional forestry policy, the area of forest plantations will increase only slightly between 2000 and 2050 (from 1.1 to 1.2 million km²). The total forest area for wood production will increase from 9.5 to 14.5 million km² (Figure 4.2.2.2, left panel).

Figure 4.2.2.3
Prevented global MSA (Mean Species Abundance) loss compared to the baseline scenario, 2000 – 2050



Source: PBL 2010

Improved forest management can contribute to reducing biodiversity loss (measured in MSA, see Section 7.2).

According to this projection, by 2050, just over a third of the global forest area will be used for wood production. The area of primary forest, defined in IMAGE as established before 1970 and not exploited since, will decrease in 2050 by more than 6 million km^2 from almost 30 million km^2 in 2000.

Policy interventions

Several policy interventions on forest management can be simulated in the IMAGE model 3.0:

- increase in production on highly productive forest plantations;
- increase in carbon storage to mitigate climate change;
- increasing harvest efficiencies, or using harvest residues for energy
- more reduced impact logging (RIL) techniques, less conventional selective felling.

The scenario study ‘Rethinking global biodiversity strategies’ implemented the following two ambition levels for improved forest management as alternatives for the baseline trend (Figures 4.2.2.2 and 4.2.2.3):

1. Moderate ambition level: partial substitution of conventional selective felling in tropical forests with RIL techniques, and forest plantations targeted at supplying 25% of the global wood demand;
2. High ambition level: full substitution of conventional selective felling with RIL techniques as of 2010, and forest plantations targeted at supplying 40% of the global wood demand by 2050. This represents a plausible future development of plantation growth (Brown, 2000).

The ambitious improvements in forest management will result in considerably less land used for forestry by 2050 (about 10 million km^2, or one third smaller area than under the baseline scenario). With the reduced forest area, and the assumed positive effects of RIL techniques, biodiversity loss caused by forestry will be reduced. For the lower ambition level, gains will be smaller with forestry area expanding well over 3 million km^2, and less biodiversity loss prevented.

4. Data, uncertainties and limitations

Data

The main data source for the development and calibration of the forest management module is FAO Forest Resource Assessment (FAO, 2010), from which data on wood production and deforested areas are derived. In addition, statistics from the International Energy Agency (IEA, 2012b) are used to estimate the regional fuelwood production, based on household fuelwood and charcoal requirements in national energy statistics. Finally, national data were collected to parameterise the type and production parameters of forest management in world regions (see details in Arets et al., 2011), and establishment of new forest plantations was designed according to planting rates reported and projected by FAO (Brown, 2000; Carle and Holmgren, 2008).

Uncertainties

Several assumptions had to be made to project future production in forest management systems. These pinpoint the uncertainties in the forestry management model. Better data, monitoring and reporting would improve calibration of the IMAGE forest management module.

FAO Forest Resource Assessment reports are published regularly on quantities of industrially produced wood and the areas of primary and secondary forests. However, these reports do not include the area from which these wood quantities are harvested, and the forest management system of these areas. The amount of wood produced in deforestation processes is not reported, probably due to the illegal nature of many such operations.

Few data are available on the extent of illegal logging, they are not captured in the FAO statistics, but in satellite-based assessments, and only very rough estimates are available (UNEP-INTERPOL, 2012). In addition, few data are available on informal collection of fuelwood in forests in developing countries (FAO, 2001a; FAO, 2008). Estimates of total fuelwood demand are highly uncertain (IEA, 2012b), and fuelwood demand is not only met by the forestry operations, but also from other sources.

Another uncertainty is the starting point, which is the state of forest use by age cohort in 1970. As forests take several decades to a century to regrow after felling, the effect of historic uncertainties in forest-use extends far into the future.

Limitations

The only driver of deforestation modelled in IMAGE 3.0 is the net expansion of agriculture per region. Many drivers of deforestation are not related to agricultural expansion, but there is no global assessment of these other drivers. Therefore, total deforestation rates are calibrated in IMAGE. Drivers and extent of deforestation are very uncertain and subject to debate, yet determine future deforestation and deforestation emissions in scenario simulations.

5. Key publications:

Arets EJMM, van der Meer PJ, Verwer CC, Hengeveld GM, Tolkamp GW, Nabuurs GJ and van Oorschot M (2011). Global wood production : assessment of industrial round wood supply from forest management systems in different global regions, Alterra, part of Wageningen University and Research Centre, Wageningen.

6. Input/Output Table

Table 4.2.2.1

Input in and output from the forest management module

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Timber demand	Demand for roundwood and pulpwood per region.	3
Forest plantation demand	Demand for forest plantation area.	3
Fraction of selective logging	The fraction of forest harvested in a grid, in clear cutting, selective cutting, wood plantations and additional deforestation. Fraction of selective cut determines the fraction of timber harvested by selective cutting of trees in semi-natural and natural forest.	3

Harvest efficiency	Fraction of harvested wood used as product, the remainder being left as residues. Specified per biomass pool and forestry management type.	3
Demand traditional biomass	Regional demand for traditional bioenergy.	4.1.1
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Carbon pools in vegetation - grid	Carbon pools in leaves, stems, branches and roots).	6.1
Land suitability - grid	Suitability of land in a grid cell for agriculture and forestry, as a function of accessibility, population density, slope and potential crop yields.	4.2.3
External datasets		
FAO deforestation rates	Historical deforestation rates according to FAO.	FAO (2010)
Traditional biomass from non-forest land	Fraction of traditional fuelwood from non-forestry sources, such as orchard, assumed to be 68% (low-income countries) and 50% (middle-income countries).	FAO (2001a); FAO (2008)
Output	**Description**	**Use (section)**
Forest management type - grid	Forest management type: clear cut, selective logging, forest plantation or additional deforestation.	6.1, 5.1
Regrowth forest area - grid	Areas of re-growing forests after agricultural abandonment or timber harvest.	5.1
Degraded forest area - grid	Permanently deforested areas for reasons other than expansion of agricultural land (calibrated to FAO deforestation statistics).	5.1
Harvested wood - grid	Wood harvested and removed.	5.1
Timber use fraction	Fractions of harvested timber entering the fast-decaying timber pool, the slow-decaying timber pool, or burnt as traditional biofuels.	6.1
Forest residues - grid	Residues from timber harvest, left in forest after harvest or used as bioenergy.	Final output

4.2.3 Land-use allocation

Elke Stehfest, Koen Overmars, Jonathan Doelman, Peter Verburg

Key policy issues:

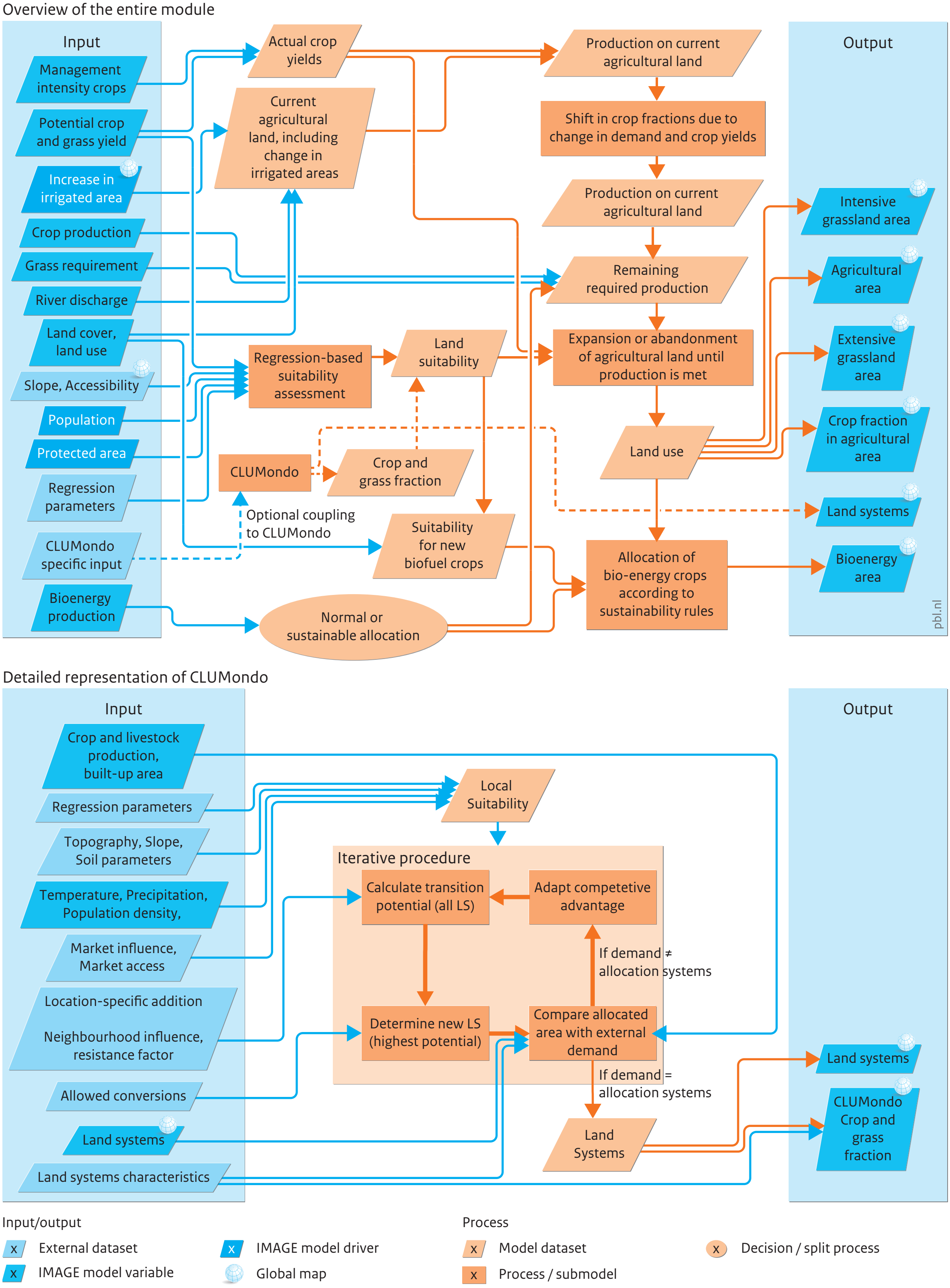
- How will changes in agricultural demand and trade affect future land-use patterns?
- How will land-use regulation, such as protected areas and REDD schemes, affect future land use and the impacts of land-use change?
- How can agricultural intensification increase global food production, and what policies will contribute to this?

1. Introduction

About one third of the Earth's land area is under cropland and pasture. The proportion of areas suitable for agriculture that is already in use is even larger. Humans strongly depend on agricultural production, as supported by soils and climatic circumstances, and thus need to rely on a continued functioning of these systems. At the same time, major environmental problems rise from the size and intensity of agricultural land use, for example greenhouse gas emissions, distortions of the nutrient and water cycles, and biodiversity loss. Total agricultural area, globally or in a region, may be sufficient to assess the first order effects of production potential and environmental impacts. However, the location of agricultural land in a region or landscape is extremely important because yields of crops and grass depend on soil and climate, and also on spatially heterogeneous socio-economic factors, and because many impacts are location dependent.

The location of new agricultural area determines the vegetation type removed, and thus the amount of carbon emitted, and the biodiversity impacts related to a loss of the vegetation type. Extreme examples of location-specific impacts are conversion of carbon- and species-rich peatland and wetlands. Other factors include the impact of agriculture on nutrient and water cycles, and location characteristics such as soil properties and slope. As well as the location, the composition of landscapes is a determining factor because how land uses are connected determines to some extent the environmental impact and the production potential. For environmental impacts, the most prominent examples of landscape composition are biodiversity effects, wind and water erosion, hydrology, and ecosystem services. Some crops benefit from nearby forests for pollination and pest control, while others suffer additional pest pressure.

Figure 4.2.3.1
Land-use allocation model in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.2.3.1).

Consequently, accurate and high resolution modelling of agricultural land use is essential in global integrated assessment.

In IMAGE, the spatial allocation of crops, pasture and bioenergy is driven by regional crop and grassland production and their respective intensity levels, as calculated by the IMAGE agro-economic model (Section 4.2.1). In addition, potential crop and grass yields (Section 6.2) and suitability factors (this Section) determine the extent and location of agricultural areas.

2. Model description

IMAGE 3.0 has two methods to represent land-use dynamics and to determine the location of new agricultural lands. For applications not focusing on land-use dynamics specifically, a simple regression-based suitability assessment is used to determine future land-use patterns. A dynamic link to CLUMondo (Van Asselen and Verburg, 2013) enables more detailed representation of land-use systems and their dynamics. Both approaches are embedded in the IMAGE land-use allocation model (Figure 4.2.3.1).

Both approaches are driven by regional crop and grassland production and their respective intensity levels, as calculated by the IMAGE agro-economic model (Section 4.2.1). Agricultural land use is allocated to grid cells in an iterative process until the required regional production of crops and grass is met. Land use in IMAGE is modelled using dominant land use per grid cell on a 5x5 minute resolution, distinguishing extensive grasslands, agricultural and non-agricultural grid cells, and within agricultural land areas fractions of grass, seven rain-fed and seven irrigated crop types, and bioenergy crops.

In each time step, maps of actual crop yields are computed by combining the potential crop and grassland yields calculated by the crop model (Section 6.2), and the regional management intensity from the agro-economic model (Section 4.2.1). Starting with the land-cover and land-use map of the previous time step, actual yields are used to determine crop and grassland production on current agricultural land. This is compared to the required regional crop and grassland production. If the demand exceeds calculated production, the agricultural area needs to be expanded at the cost of natural vegetation. If the calculated production of current cropland exceeds the required production, agricultural land is abandoned to adjust to the production required.

Crop and grassland is either abandoned or expanded until the required production is met. Since actual yields are taken into account, changes in crop yields in time due to technological change, climate change and land heterogeneity are included. If yields in the new agricultural areas are lower than average in the current area, relatively more agricultural land is required compared to the production increase.

In determining the location of agricultural expansion or abandonment, all grid cells are assessed and ranked on suitability, based on an empirical regression analysis, and optionally based on a link to CLUMondo (see further below).

Additionally, a few other rules are applied in determining the location of new agricultural land. For instance, agricultural expansion is not permitted in protected areas, and in areas otherwise protected, such as in assumed REDD (reducing emissions from deforestation and degradation) schemes. A grid cell is only regarded suitable for agriculture if the potential rain-fed production is at least 5% of the global maximum attainable crop yield. Grid cells with a production potential between 0.05 and 5% of the maximum attainable are still assumed suitable for extensive grassland.

Irrigated areas are increased on a regional scale, prescribed by external scenario-dependent assumptions, such as based on FAO (Alexandratos and Bruinsma, 2012). In each time-step, more irrigated areas are allocated in agricultural land based on the need for irrigation (the difference in rain-fed and irrigated yields), and water availability.

In agricultural areas, the fraction of specific crops is determined based on the initial fractions, and modified annually based on changes in regional demand and local crop yields. As a result, the land-use fraction of a certain crop increases when the demand for this crop increases faster than for other crops, or if the potential yield in this grid cell increases more than for other crops.

Urban built-up areas are not represented as dominant land use in IMAGE, but as a fraction of a 5x5 minutes grid cell. Historically, they are based on HYDE (Klein Goldewijk et al., 2010), and increase in the scenario period as a function of GDP and population (Chapter 3). Built-up areas mostly expand into very productive agricultural areas, leading to additional demand for agricultural area elsewhere, though this effect is small compared to other drivers of agricultural land-use change.

The land use allocation model enables new land-use and land cover maps to be created (see Section 5.1). These land-use maps specify agricultural land, extensive grassland, and land for sustainable bioenergy production. Crop fractions are allocated for all 18 crop types in IMAGE (temperate cereals, rice, maize, tropical cereals, roots and tubers, pulses, and oil crops, both rain-fed and irrigated; grass; sugar cane and maize for bioenergy; and woody and non-woody bioenergy). These data are calculated on a 5x5 minute resolution, and aggregated to proportional land use on 30 minute resolution of the carbon, crop and water model LPJmL. Additional data layers are provided when linked to CLUMondo (see further below).

Empirical regression analysis to determine land-use suitability

Land-use change is determined by various factors, such as climate and climate variability, soil and terrain characteristics, and socio-economic variables, such as population density and accessibility (O'Neill, 2013). Land-use change dynamics differ substantially between regions (Lambin et al., 2000). These characteristics are taken into account in IMAGE 3.0 in a regional suitability assessment based on an empirical multiple linear regression analysis (Doelman and Stehfest, in prep.).

The suitability assessment includes data on two biophysical determinants: the potential yield which covers effects of climate and soil (Section 6.2), and the terrain slope index (IIASA and FAO, 2012) based on SRTM elevation data (Shuttle Radar Topography Mission) from NASA. Two socio-economic determinants are included: population density (Klein Goldewijk et al., 2010), and the accessibility index from JRC (Nelson, 2008), which is defined as minutes travel time to major cities (>50,000 inhabitants).

These four independent variables are used in multiple linear regression analysis to investigate the relationship between these land-use determinants and current land use (fractions of crop and grassland in 2005 from Klein Goldewijk et al. (2011)). The analysis is performed separately for each IMAGE region, and takes into account the logarithmic relationship found for all independent variables except for potential crop yield.

For each region, between two and four variables are found to be significant explanatory factors for 2005 land use. For example, population density is a significant determinant in almost all regions. Terrain slope is a key determinant in many regions, including North America, Europe and Asia; accessibility in South America, Africa and Australia; and potential yield in the Americas, Europe and North Africa.

The region-specific regression models are used in IMAGE to calculate the suitability of land areas in annual time-steps. As well as the suitability assessment, some additional rules are applied. The suitability of strictly protected areas is substantially reduced, or these areas are regarded as entirely unsuitable based on scenario assumptions. Optionally, a small random factor can be included to account for inherent uncertainty and non-deterministic behaviour of land-use change processes, allowing the emergence of new agricultural patches. Agricultural land is expanded according to the final suitability ranking. Extensive pastures located in areas where the natural vegetation is grassland are assumed to be rather constant over time, and thus do not expand and are only abandoned as a result of climate change.

Land use in IMAGE is modelled using dominant land use types per grid cell on a 5x5 minute resolution. In reality, land use is more heterogeneous. For some applications, dominant land use on 5x5 minute resolution, or the derived proportional land use on a 30x30 minute resolution may be sufficient. However, many applications require higher resolution and additional data, such as studies on biodiversity and agricultural intensification (Verburg et al., 2012).

CLUMondo
In cooperation between the IMAGE team and land-use modelling groups at Wageningen University and VU University Amsterdam, the development of a more detailed land-use

model was explored (Letourneau et al., 2012). This finally resulted in the construction of CLUMondo at the VU University Amsterdam, which is also linked to IMAGE 3.0. CLUMondo includes data on landscape composition and heterogeneity, and land-use intensity (Van Asselen and Verburg, 2012; Van Asselen and Verburg, 2013). The model uses land systems, a concept that combines data on land cover (cropland, grassland, forest, built-up area, bare land), livestock density and agricultural intensity. These characteristics are combined in 30 land system classes (Figure 4.2.3.2).

Logistic regressions between a range of biophysical and socioeconomic indicators, and the land systems are used to determine spatially explicit suitability for these systems. In combination with additional settings on neighbourhood effects, location-specific additions and a set of rules on conversion resistance, CLUMondo uses this suitability to model land system changes (Figure 4.2.3.1, bottom). The resulting maps of land systems, with their specific characteristics on land-cover areas, livestock density, and agricultural intensity describe changes in land system dynamics over time, and can be used directly in impact models.

CLUMondo is dynamically linked to IMAGE, and the change in land systems can be used as an additional suitability criterion. Fractions of crops and intensive grasslands from CLUMondo are re-arranged in 30 minutes grid cells to dominant 5 minutes crop cells, which are then given a very high suitability ranking in IMAGE to ensure these cells are converted first. In this way, IMAGE follows the dynamics of CLUMondo in terms of location of new or abandoned agricultural land, and tries to make agricultural areas and agricultural expansion in IMAGE and CLUMondo consistent on a 30x30 minutes resolution.

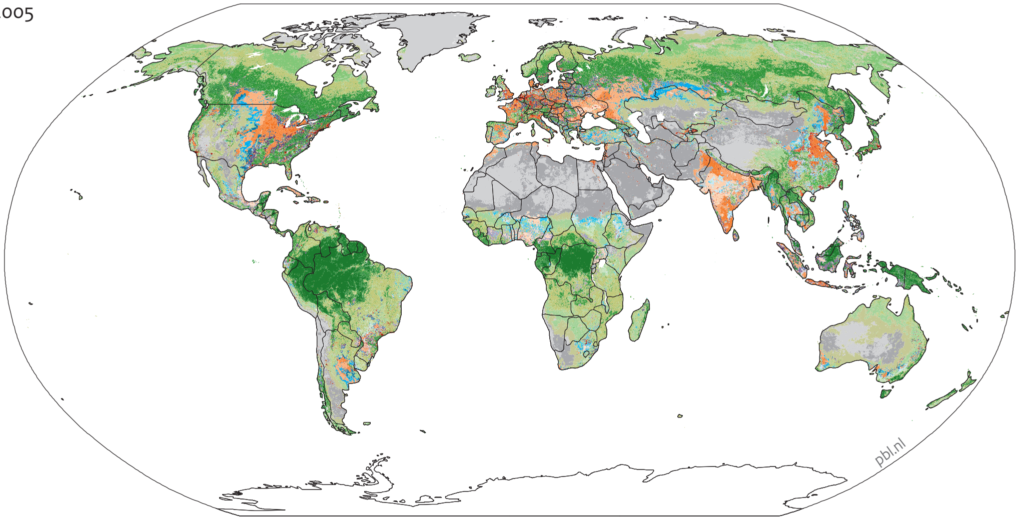
Currently, IMAGE is not using the endogenous intensification calculated by CLUMondo (Van Asselen and Verburg, 2013) because it is not necessarily consistent and is mostly lower than the intensification calculated by the agro-economic model (Section 4.2.1). At a later stage, intensification in IMAGE and CLUMondo could be made consistent via iterations or closer linkages. For similar reasons, grassland dynamics are not taken from CLUMondo but from the IMAGE livestock and agro-economic models.

3. Policy issues

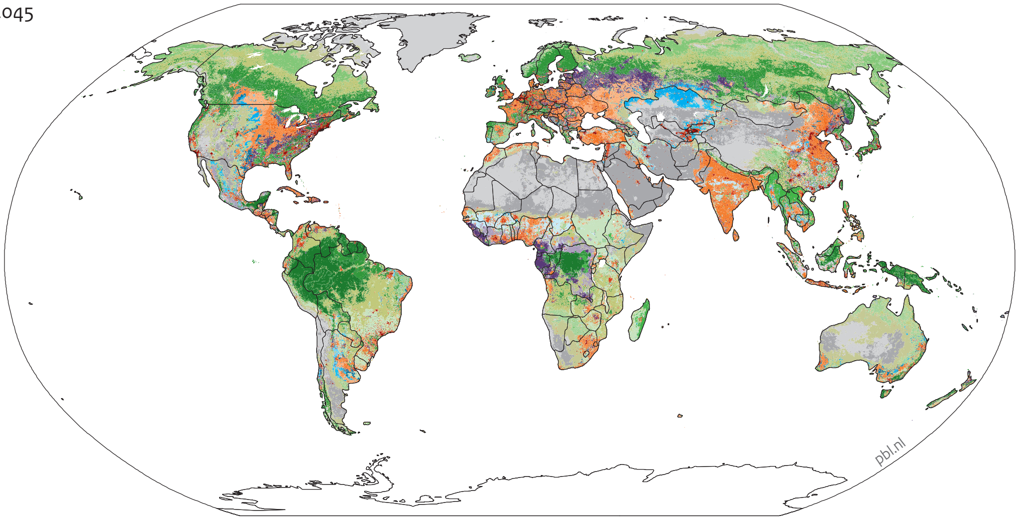
Baseline developments
In most baseline scenarios, agricultural area increases at the expense of forest and other natural areas (for instance, PBL, 2012). The land-use allocation model is used to assess where these changes may occur (Figure 4.2.3.2), and thus contributes to assessing the consequence of agricultural expansion and intensification in specific ecosystems. Agricultural land-use maps play an important role in assessing the interaction between the Human system and the Earth system (Section 5.1) and in determining location-specific biogeochemical processes and impacts (Section 7.1).

Figure 4.2.3.2
Distribution of land systems

2005



2045



Cropland systems
- Extensive with few livestock
- Extensive with bovines, goats and sheep
- Extensive with pigs and poultry
- Medium intensive with few livestock
- Medium intensive with bovines, goats and sheep
- Medium intensive with pigs and poultry
- Intensive with few livestock
- Intensive with bovines, goats and sheep
- Intensive with pigs and poultry

Bare systems
- Bare
- Bare with few livestock

Mosaic cropland and grassland systems
- With bovines, goats and sheep
- With pigs and poultry
- Extensive; with few livestock
- Medium intensive; with few livestock
- Intensive; with few livestock

Mosaic cropland and forest systems
- With pigs and poultry
- Extensive; with few livestock
- Medium intensive; with few livestock
- Intensive; with few livestock

Settlement systems
- Peri-urban and villages
- Urban

Forest systems
- Dense
- Open with few livestock
- Open with pigs and poultry

Grassland systems
- Natural
- With few livestock
- With bovines, goats and sheep

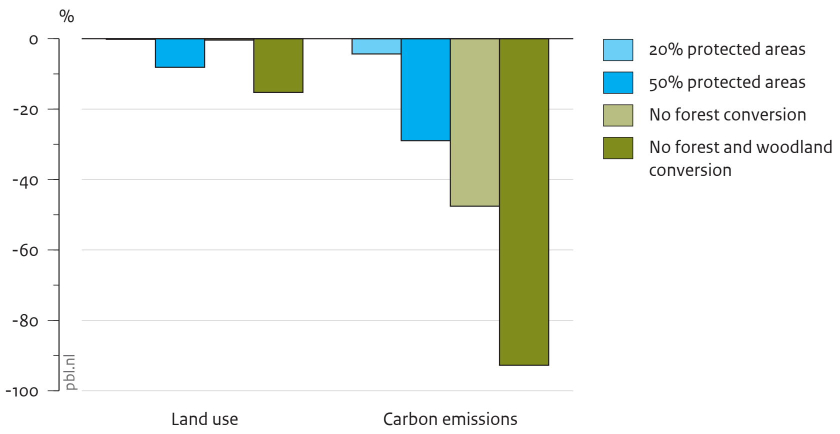
Mosaic (semi-)natural systems
- Grassland and forest
- Grassland and bare

Source: Van Asselen and Verburg 2013, PBL 2014

Dynamics of land-use expansion and intensification differ across regions.

Figure 4.2.3.3

Carbon emissions and land use under restricted land supply, compared to the baseline scenario, 2020



Source: PBL 2014

The effect of additional protected areas on land use and carbon emissions strongly depends on the type of vegetation protected. Preventing forest conversions will reduce carbon emissions, but not necessarily agricultural land use.

Policy interventions

Many policy interventions that relate to agricultural systems are implemented in the agro-economic model (Section 4.2.1), and affect land use and land-use patterns via changes in agricultural production and intensification. Key examples are agricultural policies and trade liberalisation, biofuel policies, dietary changes, and agricultural intensification. Other policy interventions mainly relate to land-use regulation and land supply, for example by expanding protected areas and protecting forests under REDD schemes. These measures lead to reduced land supply and higher land and commodity prices in the agro-economic model, and thereby change agricultural demand and production. Land-use patterns are then affected by land-use regulations as regional agricultural production changes, but also as location-specific allocation is different under such regulations (see also Section 8.3).

In a study using the OECD Environmental Outlook scenario, IMAGE was used to evaluate impacts of protection levels of natural areas: on top of a baseline scenario with strong bioenergy mandates, it was assumed that 20% or 50% of the land area were protected as nature reserves (covering various types of vegetation), or that all forests or all forests and woodland were protected from agricultural expansion (Figure 4.2.3.3). The relative reduction in land use and CO_2 emissions differ greatly depending on the type of areas protected. If forests are protected, almost the same amount of agricultural land is used by switching to non-forested land. Thus CO_2 emissions are reduced, but reduction in land use and related biodiversity loss is much less.

4. Data, uncertainties and limitations

Data
As the starting point for the simulation in 1970, HYDE land use data were aggregated to dominant land-use types on a 5 minute grid scale. For the period 1970–2005, the model can either allocate land use based the dynamic behaviour described above, or be constrained by the HYDE land use map in 2005. The latter option is used mainly when specific impact models require a close match between IMAGE land-use patterns and observations in 2005 (Hurtt et al., 2011). Other data sources include maps of protected areas (IUCN, 2009; UNEP, 2011), accessibility (Nelson, 2008), and irrigated areas (Siebert et al., 2005), all aggregated to the IMAGE 5 minute grid. The trend for future irrigated areas is often based on FAO projections (Alexandratos and Bruinsma, 2012).

Uncertainties
The main uncertainty in land-use allocation obviously relates to the location of new agricultural land and land abandonment, and the effect on impacts and feedback. Global land-use change models are rarely validated, because adequate data for evaluation are not available. For instance, differences in satellite-based land-use maps for different time steps often relate to differences in methodologies, rather than to real transformation processes (Hansen et al., 2008). However, the need for evaluation is increasingly acknowledged, and with improved data availability, such assessments now become possible (Hansen et al., 2013).

Impacts and feedbacks of land-use change depend to differing degrees on the location. For carbon emissions, the vegetation type and carbon content at the location of agricultural expansion is decisive, while the exact location of the new land is less relevant. Likewise for feedback to agricultural production, the attainable crop yields are more relevant than the exact location. Some impacts (e.g., on biodiversity) depend more on small-scale processes and landscape composition, which are currently not included in most integrated assessment models. To evaluate the IMAGE land-use allocation model, the simulated locations of new agricultural land need to be compared to empirical data on land cover transitions, or to maps of land-cover change (e.g. Hansen et al. 2013).

Another key uncertainty is the relation between agricultural intensification of expansion, when demand increases. So far, their relative contribution is calculated in MAGNET, but could be informed by the smaller scale land system models.

Limitations
A key limitation of the current land-use allocation model is the limited feedback to the agricultural economy. The suitability of land feeds back to agricultural production only for regional averages. The spatial heterogeneity of land management in a region, which determines many environmental impacts such as nutrient imbalances and biodiversity, can be addressed by using the CLU-Mondo module.

5. Key Publications

Van Asselen S and Verburg PH. (2013). Land cover change or land-use intensification: simulating land system change with a global-scale land change model. *Global Change Biology* 19(12), pp. 3648–3667, DOI: 10.1111/gcb.12331.

Verburg PH, van Asselen S, van der Zanden EH and Stehfest E. (2012). The representation of landscapes in global scale assessments of environmental change. *Landscape Ecology*, pp. 1–14.

Doelman JC and Stehfest E (in prep.). Empirical land suitability assessment for spatial allocation of land use *(available on request)*. PBL Netherlands Environmental Assessment Agency, PBL, Bilthoven/The Hague.

6. Input/Output Table

Table 4.2.3.1
Input in and output from the land-use allocation model in IMAGE

Input	**Description**	**Source (section/ other)**
IMAGE model drivers and variables		
Population - grid	Number of people per gridcell (using downscaling).	3
Increase in irrigated area - grid	Increase in irrigated area, often based on external projections (e.g., FAO).	3
Protected area - grid	Map of protected nature areas, limiting use of this area.	3
Crop production	Regional production per crop.	4.2.1
Grass requirement	Grass requirement for ruminants (non-dairy cattle, dairy cattle, sheep and goats) in pastoral and mixed systems.	4.2.4
Bioenergy production	Total bioenergy production.	4.1.3
Management intensity crops	Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions - current practice and technological change in agriculture - and is endogenously adapted in the agro-economic model.	4.2.1

Potential crop and grass yield - grid	Potential crop and grass yield, changing with time due to climate change and possibly soil degradation.	6.2
River discharge - grid	Average flow of water through each grid cell.	6.3
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
External datasets		
Accessibility - grid	Accessibility expressed as travel time.	Nelson (2008)
Slope - grid	Terrain slope index.	(IIASA and FAO, 2012)
Regression parameters	Regression parameters of suitability assessment.	Doelman and Stehfest (in prep.)
Other crops	Fraction of other, not modelled crops in agricultural area, assumed constant in the future.	FAOSTAT database
CLUmondo specific input - grid	CLUMondo specific input.	Van Asselen and Verburg (2013)
Output	**Description**	**Use (section)**
Agricultural area - grid	Total area for crop production (annual and perennial) and intensive grassland.	5.1
Crop fraction in agricultural area - grid	Fraction of agricultural land by crop type, per grid cell.	5.1
Bioenergy area	Area of bioenergy crop production, in model setting where sustainability criteria require that the area for bioenergy crops is not included in the agricultural production area (to avoid competition between bioenergy and food).	5.1
Intensive grassland area	Intensively used grassland areas for grazing or mowing, at locations also suitable for crop production.	5.1
Extensive grassland area - grid	Extensive pasture with low productivity used for grazing.	5.1
Land systems - grid	Thirty land systems as defined in CLUMondo (Van Asselen and Verburg, 2012), characterized by specific levels of built-up area, cropland area, livestock density and management intensity.	5.1
Land suitability - grid	Suitability of land in a grid cell for agriculture and forestry, as a function of accessibility, population density, slope and potential crop yields.	4.2.2

4.2.4 Livestock systems

Lex Bouwman

Key policy issues

– What are the impacts of increasing livestock production on land use, greenhouse gases and other emissions to air and surface water?
– How does the use of marginal lands for grazing increase the risk of degradation and loss of productivity, inducing more forest clearing?

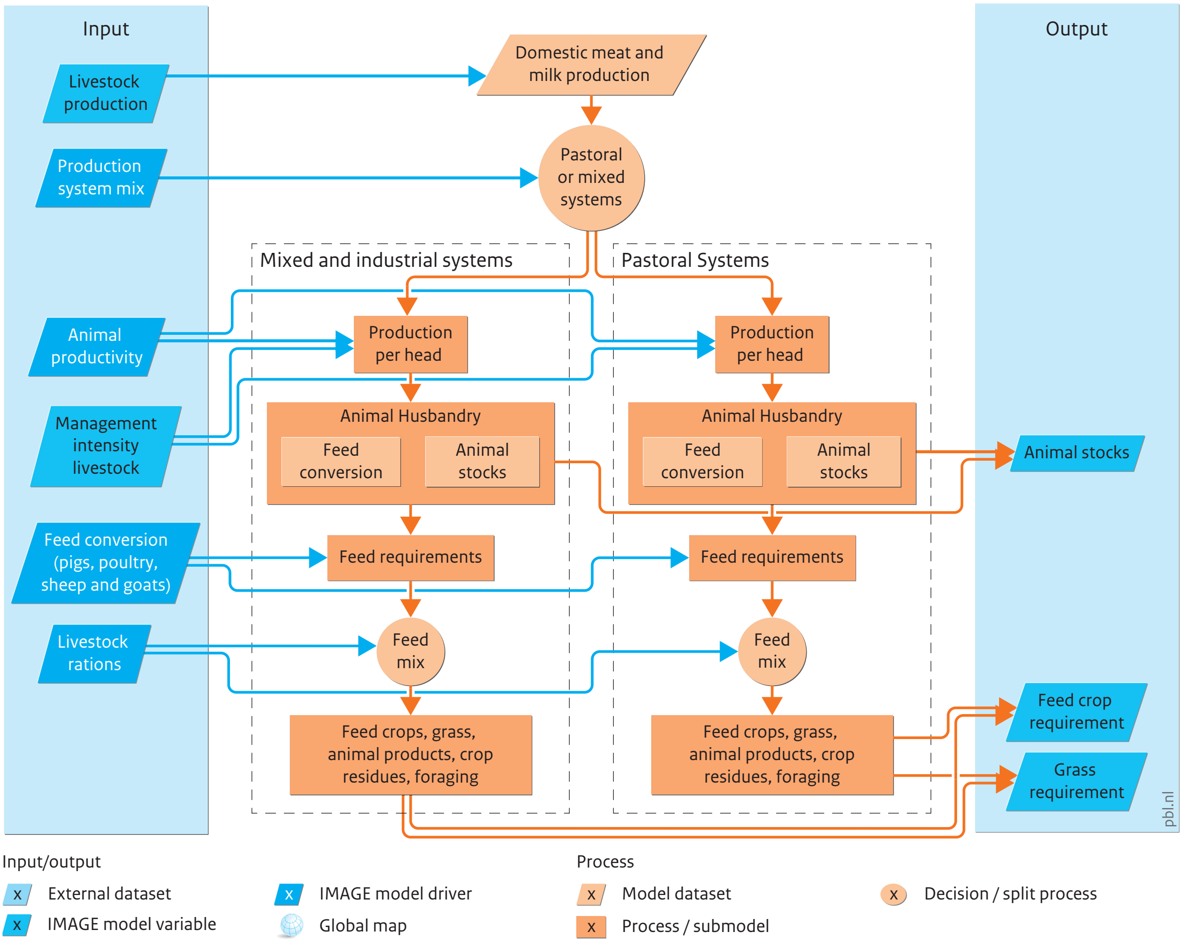
1. Introduction

Food production will have to increase in order to feed the world's growing population. However, with increasing prosperity and falling production costs, dietary patterns are shifting to include a higher proportion of meat and milk. In the last few decades, traditional mixed farming systems have not been able to raise production levels sufficiently to meet increasing demand. Consequently, modern livestock production systems are expanding rapidly particularly for poultry and pork, creating growing demand for feed crops. This trend started in high-income countries and is now observed in emerging and developing countries (Alexandratos and Bruinsma, 2012).

Interactions between crop and livestock production are described in the livestock systems module of IMAGE, and also the consequences of changing practices in livestock farming for production of food crops and grass. For this purpose, IMAGE distinguishes pastoral livestock systems, and mixed and landless (industrial) production systems. Pastoral systems are based on grazing ruminants, while mixed and landless systems integrate crop and livestock production in which livestock are fed a mix of crops, crop by-products, grass, fodder and crop residues (Bouwman et al., 2005; Bouwman et al., 2006).

Livestock production is related to a wide range of the environmental issues, and the consequences of changes in the livestock system can be studied in the IMAGE:
(i) Expansion of grazing land and particularly arable land for feed crop production is required to support increasing livestock numbers. According to Bouwman et al. (2005) most arable land expansion is to increase feed production;
(ii) Large amounts of methane (CH_4) emitted by ruminants during enteric fermentation are the second major source of greenhouse gas emissions after CO_2;
(iii) Excreta from all livestock categories is a source of ammonia, methane, nitrous oxide and nitric oxide;
(iv) Odour nuisance and nitrate leaching to groundwater are major local-scale problems;

Figure 4.2.4.1
Livestock systems module in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 4.2.4.1).

(v) A significant amount of land used for ruminants grazing is marginal, low-productive grassland with low carrying capacity and high risk of degradation due to over-grazing, especially in arid and semi-arid regions (Seré and Steinfeld, 1996; Delgado et al., 1999). To compensate for productivity losses in these areas, forests may be cleared to expand agricultural land areas.

2. Model description

Livestock production

IMAGE distinguishes two livestock production systems (Figure 4.2.4.1), namely pastoral systems, and mixed and industrial systems, based on FAO (Seré and Steinfeld, 1996). Pastoral systems are mostly dominated by extensive ruminant production, while mixed and industrial systems are more intensive with animal husbandry comprising grazing ruminants and monogastrics. The distribution of livestock production in the two systems is constructed from historical data for the years up to the present, and for future years will depend on the scenario selected.

Livestock

IMAGE distinguishes five types of livestock: beef, dairy cattle (both large ruminants), the category sheep & goats (small ruminants), pigs, and poultry (both monogastrics). The numbers of animals and the proportion per production system are calculated from data on domestic livestock production per region provided by the agro-economic model MAGNET (Section 4.2.1). The number of animals in each of the five livestock types is calculated from the total production per region and the characteristics of the livestock systems in that region.

Stocks of dairy cows (POP) per country and world region are obtained from total milk production (PROD) and milk production per animal (MPH):

$$POP_{dairy} = PROD_{dairy} / MPH \qquad (4.2.4.1)$$

Animal stocks per region of beef cattle, pigs, and sheep and goats are obtained from production and carcass weight (CW) and off-take rate (OR):

$$POP = PROD / (OR*CW) \qquad (4.2.4.2)$$

Historical data on milk production per cow, off-take rate, and carcass weight are obtained from statistics, and values for future years will depend on the scenario selected.

Energy requirements

For dairy cattle, the energy requirements are calculated for maintenance (based on body weight), feeding (based on the proportion of grass in feed rations), lactation (based on milk production per cow) and pregnancy (based on the number of calves per year). The amount of feed dry matter is calculated on the basis of the proportion of digestible energy in the total energy intake, and the energy content of biomass.

Energy requirements for cattle are based on animal activity and production, and for pigs, poultry, sheep and goats on Feed Conversion Ratios (FCR). This is the amount of feed (kg dry matter) required to produce one kilogram of milk or meat. The FCR values are based on historical data and values for future years will depend on the scenario selected.

Cropland and grassland required

Areas for feed crop production and grass are calculated on the basis of feed crop and grass requirements (see Section 4.2.3, Land-use allocation), which are calculated from total feed requirement and diet composition (feed rations, see below).

Composition of animal feed

IMAGE distinguishes five feed categories:

(i) grass, including hay and grass silage;
(ii) feed crops and processing by-products;
(iii) crop residues in the field after harvesting, and fodder crops;
(iv) animal products;
(v) foraging including roadside grazing, scavenging household waste, and feedstuffs from backyard farming.

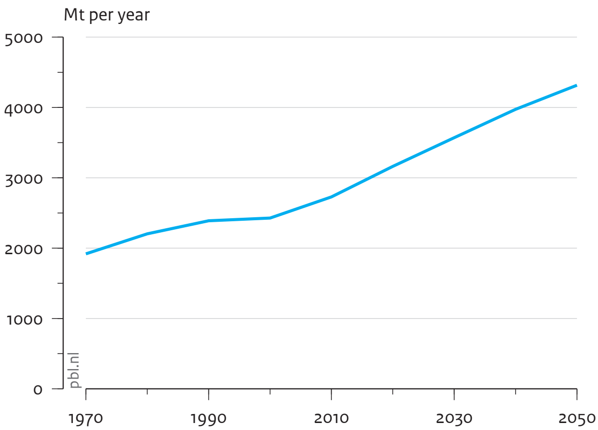
In pastoral ruminant production systems, the feed is almost entirely grass except in developing regions where foraging constitutes a larger but variable proportion of the total feed. Pigs and poultry are fed feed crops and by-products, crop residues and fodder. Since these animals are mainly farmed in mixed systems, the contribution of feed crops and residues to the total feed in these systems is much higher than in pastoral systems.

The required feed crop production per animal is calculated from feed rations, and this information is incorporated into the agro-economic model (Section 4.2.1). The proportion of grass in feed rations determines total grass consumption, which is used to compute the grassland area per world region, based on grazing intensity (Sections 4.2.1 and 4.2.3).

Scenario definition

A scenario includes assumptions on milk production per animal for dairy cattle, carcass weight and off-take rate for beef cattle, pigs, poultry, sheep and goats, and feed conversion rates (FCR) for pigs, poultry, sheep and goats. The changes in these parameters are generally based on the scenario storyline, and on the economic growth scenario.

Figure 4.2.4.2
Global grass consumption under a baseline scenario



Source: PBL 2012

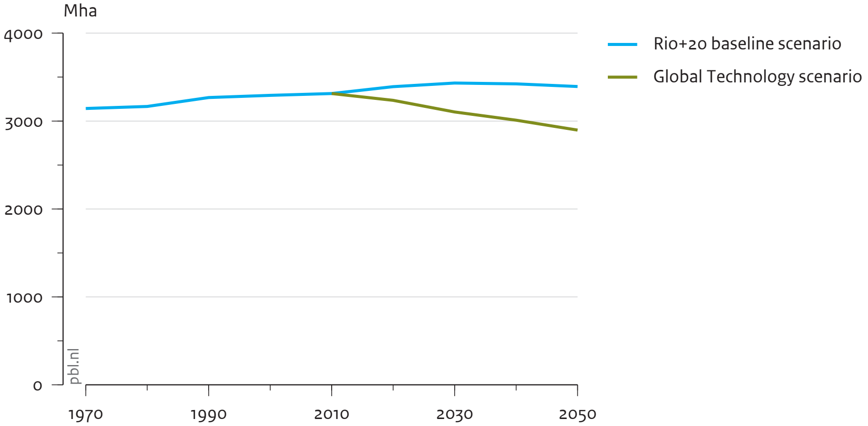
Despite a shift towards compound feed, global grass consumption in livestock systems is projected to increase (PBL, 2012).

3. Policy issues

Baseline developments
Between 1970 and 2010, global grass consumption increased by more than 40% (Figure 4.2.4.2), while global grassland area only increased about 5% from 3134 to 3313 million hectares in the same period (Figure 4.2.4.3). The global area of pastoral grassland only shows slight and gradual changes.

While extensive pastoral production systems have changed little, mixed and industrial systems have moved rapidly towards intensification. Most baseline scenarios indicate that a similar slow increase in grassland area is required over the coming decades as observed historically. Under the baseline scenario from the Rio+20 study, these developments result in a small increase of 2% in global grassland area (Figure 4.2.4.3), but this will require considerable productivity increases in many parts of the world as discussed in Bouwman et al. (2005).

Figure 4.2.4.3
Global grassland area under baseline and sustainability scenario



Source: PBL 2012

Future trends in grassland areas strongly depend on grassland management and livestock productivity (PBL, 2012).

Policy interventions

Several policy interventions can introduce changes in livestock systems compared to the baseline:

- A larger proportion of livestock production in mixed systems will inherently increase overall feed conversion ratios of ruminants;
- Production parameters, such as milk production per animal, carcass weight and off-take rates, will have an effect on the feed conversion ratio, which in general will be lower in more productive animals;
- Higher feed conversion ratio of small ruminants, such as sheep and goats, will reduce demand for grass;
- The proportion of grass in the feed for cattle, and sheep and goats will decrease with the use of feed crops;
- More intensive grazing will require improved grassland management, including use of grass-clover mixes and fertilisers, and aligning the grazing season with grass production and rotations.

All such interventions have been combined in the Global Technology (GT) scenario of the Rio+20 study, resulting in more production in mixed systems (+10%), higher carcass weights (+10%), higher off-take rates (+10%), more efficient feed conversion by sheep and goats (+10%), more feed crops (15%) and higher grazing intensities (15%). This package leads to a considerable reduction in grassland area of about 15% compared to the baseline scenario for 2050 (Figure 4.2.4.3), leaving more area for biodiversity recovery.

4. Data, uncertainties and limitations

Data

Livestock numbers, milk production per animal, off-take rates and carcass weights for the 1970–2005 period were obtained from FAO (2012a). Various animal production systems, and the total livestock population and production have been defined in recent FAO publications (Seré and Steinfeld, 1996). For ruminants, these production systems include pastoral, mixed and landless production in various agro-ecological zones. These data have been aggregated to two systems, pastoral, and mixed & landless production systems, and disaggregated from seven world regions to the 24 world regions in the IMAGE model (Bouwman et al., 2005).

Uncertainties

There are several uncertainties in the calculation of livestock production in the different systems for historical years and scenarios. The first uncertainty is the aggregation level on the scale of country or world region, which does not take account of underlying heterogeneity. The second uncertainty concerns the use of average data for carcass weight, off-take rate, and milk production for total livestock populations. In reality, livestock populations cover different age classes, and not all animals in a population are productive. Calculations, such as energy requirement for maintenance, are a non-linear function of body weight, and thus use of average values may lead to distortion. The third uncertainty is associated with livestock numbers. Methodology and frequency of data collection (e.g., by census) vary between countries, and are probably less certain for some developing countries than for industrialised countries. This uncertainty on livestock numbers affects not only the livestock systems module, but also all IMAGE impact components that depend on livestock numbers, such as ammonia emissions (Beusen et al., 2008).

The main uncertainties in construction scenarios concern agricultural demand (Section 4.2.1), the distribution of production over the two systems, production characteristics per system, including feed requirements and feed types, and future grassland productivity and management.

Limitations

The key limitation in the current livestock module is that the ruminant livestock system has a soft linkage to the agro-economic model MAGNET (Section 4.2.1). Although MAGNET has some representation of feed substitution and intensification as a result of land scarcity, and mimics the dynamics described here, there is no explicit representation of livestock systems, and physically based feed compositions.

5. Key publications

Bouwman AF, Van der Hoek KW, Eickhout B and Soenario I. (2005). Exploring changes in world ruminant production systems. *Agricultural Systems* 84(2), pp. 121–153, DOI: 10.1016 j.agsy 2004.05.006.

6. Input/Output Table

Table 4.2.4.1
Input in and output from the livestock systems module in IMAGE

Input	**Description**	**Source (section/ other)**
IMAGE model drivers and variables		
Production system mix	Livestock production is distributed over two systems (intensive: mixed and industrial; extensive: pastoral grazing), with specific intensities, rations and feed conversion ratios.	3
Animal productivity	Effective production of livestock commodities per animal per year.	3
Feed conversion	Measure of an animal's efficiency in converting feed mass into the desired output such as meat and milk (for cattle, poultry, pigs, sheep and goats).	3
Livestock rations	Determines the feed requirements per feed type (feed crops; crop residues; grass and fodder; animal products; foraging), specified per animal type and production system (extensive/intensive).	3
Livestock production	Production of livestock products (dairy, beef, sheep and goats, pigs, poultry).	4.2.1
Management intensity livestock	Management intensity of livestock, based current practice and technological change in livestock sectors, describing carcass weight and feed requirements of livestock.	4.2.1
Output	**Description**	**Use (section)**
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	5.2, 6.4
Grass requirement	Grass requirement for ruminants (non-dairy cattle, dairy cattle, sheep and goats) in pastoral and mixed systems.	4.2.3
Feed crop requirement	Crops required for feeding livestock.	5.2

INTERACTION

INTERACTION

5 Interaction between the Human and the Earth system

5.1

5.1 Land cover and land use

Elke Stehfest

1. Introduction

In addition to emissions, land cover and land use are key linkages between the Human system and the Earth system. Land cover and use are changed by humans for a variety of purposes, such as to produce food, fibres, timber and energy, to raise animals, for shelter and housing, transport infrastructure, tourism, and recreation. These human activities have affected most areas in the world, transforming natural areas to human-dominated landscapes, changing ecosystem structure and species distribution, and water, nutrient and carbon cycles. Natural landscape characteristics and land cover also affect humans, determining suitable areas for settlement and agriculture, and delivering a wide range of ecosystem services. As such, land cover and land use can be understood as the complex description of the state and processes in a land system in a certain location. It results from the interplay of natural and human processes, such as crop cultivation, fertiliser input, livestock density, type of natural vegetation, forest management history, and built-up areas.

In IMAGE, elements of land cover and land use are calculated in several components, namely in land-use allocation, forest management, livestock systems, carbon cycle and natural vegetation. The output from these components forms a description of gridded global land cover and land use that is used in these and other components of IMAGE. In addition, this description of gridded land cover and land use per time step can be provided as IMAGE scenario information to partners and other models for their specific assessments.

2. Model description

Land cover and land use described in an IMAGE scenario is a compilation of output from various IMAGE components. This compilation provides insight into key processes in land-use change described in the model and an overview of all gridded land-cover and land-use information available in IMAGE (Table 5.1.1).

Land cover and land use is also the basis for the land availability assessment, which provides information on regional land supply to the agro-economic model

(Section 4.2.1), based on potential crop yields, protected areas, and external datasets such as slope, soil properties, and wetlands (Mandryk et al., in prep.).

3. Key publications

Mandryk M, Doelman J.C. and Stehfest E. (in prep.). Assessment of global land availability and suitability: land supply for agriculture, FOODSECURE working paper. *(available on request)*.

4. Input/Output Table

Table 5.1.1: IMAGE model variables combined to global land cover and land use.

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Protected area - grid	Map of protected nature areas, limiting use of this area.	3
Built-up area - grid	Urban built-up area per grid cell, excluded from all biophysical modelling in IMAGE, increasing over time as a function of urban population and a country- and scenario-specific urban density curve.	3
Agricultural area - grid	Total area for crop production (annual and perennial) and intensive grassland.	4.2.3
Fallow land - grid	*Fallow land*	4.2.3
Crop fraction in agricultural area - grid	Fraction of agricultural land by crop type (7 crop groups (irrigated and rainfed separately per group), 4 bioenergy crops, and other crops), per grid cell.	4.2.3
Intensive grassland area - grid	Intensively used grassland areas for grazing or mowing, at locations also suitable for crop production.	4.2.3
Extensive grassland area - grid	Extensive pasture with low productivity used for grazing.	4.2.3
Bioenergy area - grid	Area of bioenergy crop production, in model setting where sustainability criteria require that the area for bioenergy crops is not included in the agricultural production area (to avoid competition between bioenergy and food).	4.2.3
Management intensity crops - grid	Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions - current practice and technological change in agriculture - and is endogenously adapted in the agro-economic model.	4.2.1

Livestock numbers - grid	*Livestock number for 5 livestock categories (beef, dairy, sheep&goat, pigs, poultry)*	4.2.4
Management intensity livestock - grid	Management intensity of livestock, based current practice and technological change in livestock sectors, describing carcass weight and feed requirements of livestock.	4.2.1
Manure input - grid	*Manure input to pasture and cropland pasture, specified per crop type*	6.4
Fertiliser input - grid	*Fertiliser input to pasture and cropland pasture, specified per crop type*	6.4
Agricultural yields - grid	*Potential and actual yields for grass and crop type*	6.2
Planting dates - grid	*Calculated planting dates per crop type, adapted to climate change.*	6.2
Land systems - grid	Thirty land systems as defined in CLUMondo (Van Asselen and Verburg, 2012), characterized by specific levels of built-up area, cropland area, livestock density and management intensity.	4.2.3
Irrigation water withdrawal - grid	Water withdrawn for irrigation, not necessarily equal to irrigation water demand, because of limited water availability in rivers, lakes, reservoirs and other sources.	6.3
Water withdrawal other sectors - grid	Total annual water withdrawal by non-agricultural sectors.	6.3
Potential natural vegetation - grid	Potential natural vegetation type/biome, based on distribution of plant functional types.	6.1
Forest management type - grid	Forest management type: clear cut, selective logging, forest plantation or additional deforestation.	4.2.2
Regrowth forest area - grid	Areas of re-growing forests after agricultural abandonment or timber harvest.	4.2.2
Harvested wood - grid	Wood harvested and removed.	4.2.2
Degraded forest area - grid	Permanently deforested areas for reasons other than expansion of agricultural land (calibrated to FAO deforestation statistics).	4.2.2
Change in soil properties - grid	Change in soil properties, such as clay/sand content, organic carbon content, soil depth (topsoil/subsoil).	7.5
Carbon pools in vegetation - grid	Carbon pools in leaves, stems, branches and roots).	6.1
Carbon pools in soil and timber - grid	Carbon biomass in three soil pools (litter, humus and charcoal) and two timber pools (slow decaying, and fast decaying).	6.1
NPP (net primary production) - grid	CO_2 sequestered by plants and incorporated in new tissue in plant carbon pools.	6.1
MSA (mean species abundance) - grid	Mean Species Abundance (MSA) relative to the natural state of original species.	7.2

Output	Description	Use (section)
Land supply for bioenergy - grid	Land available for sustainable bioenergy production (abandoned agricultural land and non-forested land).	4.1.3
Land supply	Available land for agriculture, per grid or region, depending on suitability for crops, and excluding unsuitable areas such as steep slopes, wetlands and protected areas.	4.2.1
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	4.2.2, 4.2.3, 5.2, 6.2, 6.4, 7.3, 7.4, 7.5

Variables in italics are not explicitly reported as output in the respective section, but are nevertheless available from this model component.

5.2 Emissions

**Detlef van Vuuren, Lex Bouwman, Elke Stehfest,
Sietske van der Sluis, Olivia Braspenning Radu**

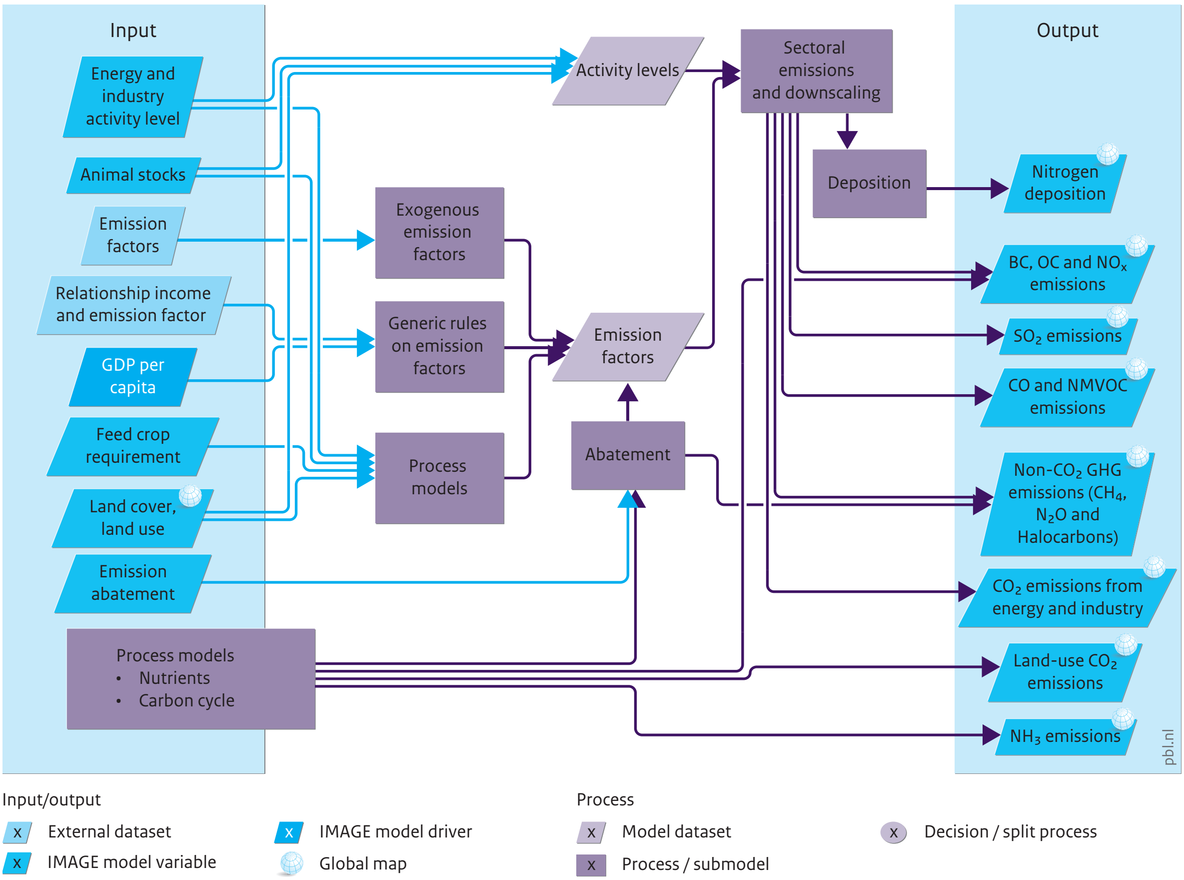
Key policy issues:

- How will emissions of greenhouse gases and air pollutants develop in scenarios with and without policy interventions, such as climate policy and air pollution control?
- What synergies between climate policy and air pollution control can be identified?

1. Introduction

Emissions of greenhouse gases and air pollutants are major contributors to environmental impacts, such as climate change, acidification, eutrophication, urban air pollution and water pollution. These emissions stem from anthropogenic and natural sources. Anthropogenic sources include energy production and consumption, industrial processes, agriculture and land-use change, while natural sources include wetlands, oceans and unmanaged land. Better understanding the drivers of these emissions and the impact of abatement measures is needed in developing policy interventions to reduce long-term environmental impacts.

Figure 5.2.1
Emission module of IMAGE 3.0



Source: PBL 2014

Anthropogenic sources, for natural sources see Table 5.2.2. More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 5.2.1).

2. Model description

General approaches

Air pollution emission sources included in IMAGE are listed in Table 5.2.2, and emissions transported in water (nitrate, phosphorus) are discussed in Section 6.4. In approach and spatial detail, gaseous emissions are represented in IMAGE in four ways:

- *World number* (W). The simplest way to estimate emissions in IMAGE is to use global estimates from the literature. This approach is used for natural sources that cannot be modelled explicitly (Table 5.2.2).
- *Emission factor* (EF). Past and future developments in anthropogenic emissions are estimated on the basis of projected changes in activity and emissions per unit of activity (Figure 5.2.1).
  The equation for this emission factor approach is:

  $$\text{Emission} = \text{Activity}_{r,i} * \text{EF-base}_{r,i} * \text{AF}_{r,i} \qquad (5.2.1)$$

  where Emission is the emission of the specific gas or aerosol; Activity is the energy input or agricultural activity; r is the index for region; i is the index for further specification (sector, energy carrier); EF-base is the emission factor in the baseline; and AF is the abatement factor (reduction in the baseline emission factor as a result of climate policy). The emission factors are time-dependent, representing changes in technology and air pollution control and climate mitigation policies.
  The emission factor is used to calculate energy and industry emissions, and agriculture, waste and land-use related emissions. Following Equation 5.2.1, there is a direct relationship between level of economic activity and emission level. Shifts in economic activity (e.g., use of natural gas instead of coal) may influence total emissions. Finally, emissions can change as a result of changes in emission factors (EF) and climate policy (AF).
- *Gridded emission factor with spatial distribution* (GEF) is a special case of the EF method, where the activity is grid-specific, resulting in grid-specific emissions. This is done for a number of sources, such as emissions from livestock (Table 5.2.2).
- *Gridded model* (GM). Land-use related emissions of NH_3, N_2O and NO are calculated with grid-specific models (Figure 5.2.1). The models included in IMAGE are simple regression models that generate an emission factor (Figure 5.2.1). For comparison with other models, IMAGE also includes the N_2O methodology generally proposed by IPCC (IPCC, 2006).

The approaches used to calculate emissions from energy production and use, industrial processes and land-use related sources are discussed in more detail below.

Table 5.2.2

Atmospheric emissions calculated in IMAGE, by source and method applied

Source	Activity	CO_2	CH_4	N_2O	SO_2	NO_x	CO	NMVOC	F-gases	BC	OC	NH_3
a). Energy-related												
End-use energy use (industry, transport, residential, services and other)	Energy consumption rates	EF	EF	EF	EF	EF	EF	EF		EF	EF	
Energy sector (production of power, hydrogen, coal, oil, gas, bioenergy)	Energy production rates	EF	EF	EF	EF	EF	EF	EF		EF	EF	
Energy transport	Energy transport rates		EF									
Other energy conversion	Energy conversion rates	EF	EF	EF	EF	EF	EF	EF		EF		
b). Industry-related												
Emissions from industrial process	Industry value added (IVA)	EF	EF	EF	EF	EF	EF	EF	EF	EF		
Cement and Steel	Regional production	EF										
c). Agriculture-, waste- and land-use related												
Enteric fermentation, cattle	Feed type and amount		GM[a]									
Animal waste, all animal categories	Number of animals		GEF	GEF		GEF						GEF[b]
Landfills	Population		GEF									
Deforestation	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Agricultural waste burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Traditional biomass burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Savannah burning	Carbon burnt	GM	GEF	GEF	GEF	GEF	GEF	GEF		GEF	GEF	GEF
Domestic sewage treatment	Population, GDP		GEF	GEF								
Wetland rice fields	Area wetland rice		GEF									
Crops	N fertiliser and manure input, croptype			GM		GM						GM

Managed grassland	N fertiliser and manure input		GM		GM						GM
indirect emissions	N crops, fertiliser and manure input		GM								
Land-use change	Clearing forest areas		GM								
d). Natural sources											
Soils under natural vegetation	Net primary production		GM		GM						GEF
Natural vegetation	N/A					W	W				
Wildfires	N/A	W				W					
Oceans	N/A	W	W			W					W
Natural wetlands	N/A	W									
Termites	N/A	W									
Wild animals	N/A	W									
Methane hydrates	N/A	W									
Volcanoes	N/A	W		W							
Lightning	N/A		W		W						

Activity describes the activity level to which the emission factor is applied, or, if only GM method occurs, the main determinant for the gridded model.

Methods: W = Global emission; EF = Regional emission factor applied to the specified activity level; GEF = Grid-specific emission calculated from gridded activity level and (regional) emission factor; GM = Gridded, model-based emission (statistical or process-based model).

[a] *GM for dairy and non-dairy cattle, EF for other animal categories.*

[b] *EF for NH_3 emissions from animal houses, manure storage and grazing livestock; GM for NH_3 emissions from manure spreading.*

Emissions from energy production and use

Emission factors (Equation 5.2.1) are used for estimating emissions from energy-related sources (Table 5.2.2). In general, the Tier 1 approach from IPCC guidelines (IPCC, 2006) is used. In the energy system, emissions are calculated by multiplying energy use fluxes by time-dependent emission factors. Changes in emission factors represent, for example, technology improvements and end-of-pipe control techniques, fuel emission standards for transport, and clean-coal technologies in industry.

Based on the EDGAR emission model, emission factors for the historical period for the energy system and industrial processes are calibrated (Braspenning Radu et al., in prep.). Calibration to the EDGAR database is not always straightforward because of differences in aggregation level. The general rule is to use weighted average emission factors for aggregation. However, where this results in incomprehensible emission factors (in particular, large differences between the emission factors for the underlying technologies), specific emission factors were chosen.

Future emission factors are based on the following rules:

- Emission factors can follow an exogenous scenario, which can be based on the storyline of the scenario. In some cases, exogenous emission factor scenarios are used, such as the *Current Legislation Scenario* (CLE) developed by IIASA (for instance, Cofala et al., (2002). The CLE scenario describes the policies in different regions for the 2000–2030 period.
- Alternatively, emission factors can be derived from generic rules, one of which in IMAGE is the EKC: Environmental Kuznets Curve (Stern, 2003; Smith et al., 2005; Van Ruijven et al., 2008; Carson, 2010; Smith et al., 2011). EKC suggests that starting from low-income levels, per-capita emissions will increase with increasing per-capita income and will peak at some point and then decline. The last is driven by increasingly stringent environmental policies, and by shifts within sectors to industries with lower emissions and improved technology. Although such shifts do not necessarily lead to lower absolute emissions, average emissions per unit of energy use decline. See below, for further discussion of EKC.
- Combinations of the methods described above for a specific period, followed by additional rules based on income levels.

In IMAGE, EKC is used as an empirically observed trend, as it offers a coherent framework to describe overall trends in emissions in an Integrated Assessment context. However , it is accepted that many driving forces other than income influence future emissions. For instance, more densely populated regions are likely to have more stringent air quality standards. Moreover, technologies developed in high-income regions often tend to spread within a few years to developing regions. The generic equations in IMAGE can capture this by decreasing the threshold values over time. For CO_2 and other greenhouse gases, such as halogenated gases for which there is no evidence of EKC behaviour, IMAGE uses an explicit description of fuel use and deforestation.

The methodology for EKC scenario development applied in the energy model is based on two types of variables: income thresholds (2–3 steps); and gas- and sector-dependent reduction targets for these income levels. The income thresholds are set to historical points: the average OECD income at which air pollution control policies were introduced in these countries; and current income level in OECD countries. The model assumes that emission factors will start to decline in developing countries, when they reach the first income threshold, reflecting more efficient and cleaner technology. It also assumes that when developing countries reach the second income threshold, the emission factors will be equal to the average level in OECD regions. Beyond this income level, the model assumes further reductions, slowly converging to the minimum emission factor in OECD regions by 2030, according to projections made by IIASA under current legislation (current abatement plans). The IMAGE rules act at the level of regions, this could be seen as a limitation, but as international agreements lead countries to act as a group, this may not be an important limitation.

Emissions from industrial processes

For the industry sector, the energy model includes three categories:

– Cement and steel production. IMAGE-TIMER includes detailed demand models for these commodities (Section 4.1). Similar to those from energy use, emissions are calculated by multiplying the activity levels to exogenously set emission factors.
– Other industrial activities. Activity levels are formulated as a regional function of industry value added, and include copper production and production of solvents. Emissions are also calculated by multiplying the activity levels by the emission factors.
– For halogenated gases, the approach used was developed by Harnisch et al. (2009), which derived relationships with income for the main uses of halogenated gases (HFCs, PFCs, SF_6). In the actual use of the model, slightly updated parameters are used to better represent the projections as presented by Velders et al. (2009). The marginal abatement cost curve per gas still follows the methodology described by Harnisch et al. (2009).

Land-use related emissions

CO_2 exchanges between terrestrial ecosystems and the atmosphere computed by the LPJ model are described in Section 6.1. The land-use emissions model focuses on emissions of other compounds, including greenhouse gases (CH_4, N_2O), ozone precursors (NO_x, CO, NMVOC), acidifying compounds (SO_2, NH_3) and aerosols (SO_2, NO_3, BC, OC).

For many sources, the emission factor (Equation 5.2.1) is used (Table 5.2.2). Most emission factors for anthropogenic sources are from the EDGAR database, with time-dependent values for historical years. In the scenario period, most emission factors are constant, except for explicit climate abatement policies (see below).

There are some other exceptions: Various land-use related gaseous nitrogen emissions are modelled in grid-specific models (see further), and in several other cases, emission factors depend on the assumptions described in other parts of IMAGE. For example, enteric fermentation CH_4 emissions from non-dairy and dairy cattle are calculated on the basis of energy requirement and feed type (see Section 4.2.4). High-quality feed, such as concentrates from feed crops, have a lower CH_4 emission factor than feed with a lower protein level and a higher content of components of lower digestibility. This implies that when feed conversion ratios change, the level of CH_4 emissions will automatically change. Pigs, and sheep and goats have IPCC 2006 emission factors, which depend on the level of development of the countries. In IMAGE, agricultural productivity is used as a proxy for the development. For sheep and goats, the level of development is taken from EDGAR.

Constant emission factors may lead to decreasing emissions per unit of product, for example, when the emission factor is specified on a per-head basis. An increasing production per head may lead to a decrease in emissions per unit of product. For example, the CH_4 emission level for animal waste is a constant per animal, which leads to a decrease in emissions per unit of meat or milk when production per animal increases.

A special case is N_2O emissions after forest clearing. After deforestation, litter remaining on the soil surface as well as root material and soil organic matter decompose in the first years after clearing, which may lead to pulses of N_2O emissions. To mimic this effect, emissions in the first year after clearing are assumed to be five times the flux in the original ecosystem. Emissions decrease linearly to the level of the new ecosystem in the tenth year, usually below the flux in the original forest. For more details, see Kreileman and Bouwman (1994).

Land-related emissions of NH_3, N_2O and NO are calculated with grid-specific models.N_2O from soils under natural vegetation is calculated with the model developed by Bouwman et al. (1993). This regression model is based on temperature, a proxy for soil carbon input, soil water and oxygen status, and for net primary production. Ammonia emissions from natural vegetation are calculated from net primary production, C:N ratio and an emission factor. The model accounts for in-canopy retention of the emitted NH_3 (Bouwman et al., 1997).

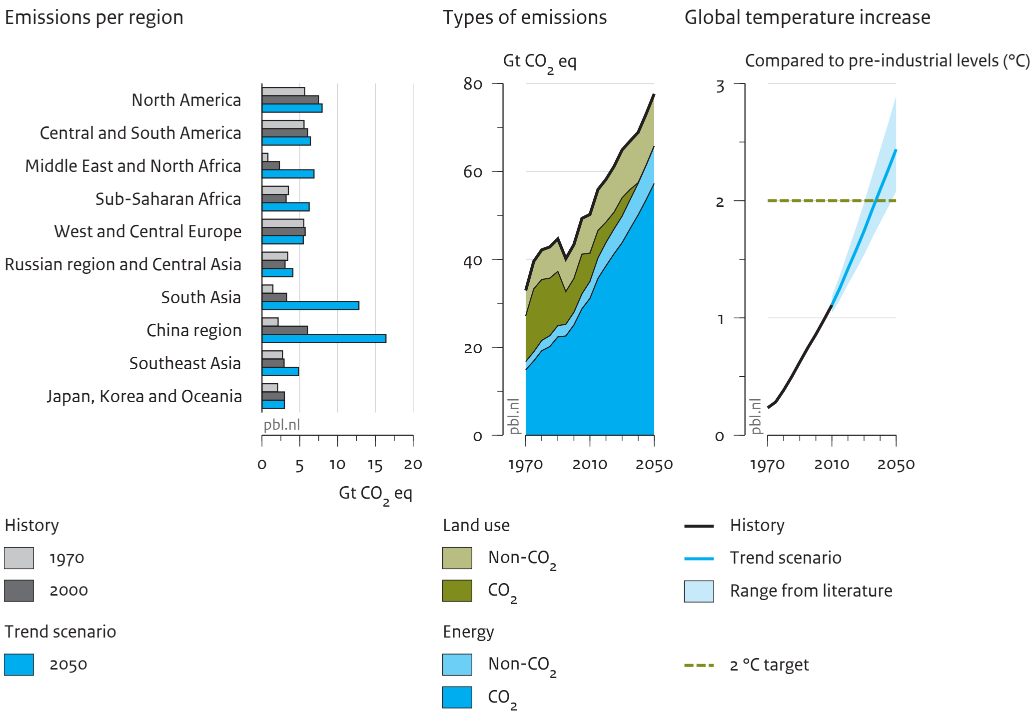
For N_2O emissions from agriculture, the determining factors in IMAGE are N application rate, climate type, soil organic carbon content, soil texture, drainage, soil pH, crop type, and fertiliser type. The main factors used to calculate NO emissions include N application rate per fertiliser type, and soil organic carbon content and soil drainage (for detailed description, see Bouwman et al. (2002a)). For NH_3 emissions from fertilised cropland and grassland, the factors used in IMAGE are crop type, fertiliser application rate per type and application mode, temperature, soil pH, and CEC (Bouwman et al., 2002a).

For comparison with other models, IMAGE also includes the N_2O methodology proposed by IPCC (2006). This methodology represents only anthropogenic emissions. For emissions from fertiliser fields this is the emission from a fertilized plot minus that from a control plot with zero fertiliser application. For this reason, soil emissions calculated with this methodology cannot be compared with the above model approaches, which yields total N_2O emissions.

Emission abatement

Emissions from energy, industry, agriculture, waste and land-use sources are also expected to vary in future years, as a result of climate policy. This is described using abatement coefficients, the values of which depend on the scenario assumptions and the stringency of climate policy described in the climate policy component. In scenarios with climate change or sustainability as the key feature in the storyline, abatement is more important than in business-as-usual scenarios. Abatement factors are used for CH_4 emissions from fossil fuel production and transport, N_2O emissions from transport,

Figure 5.2.2
Global greenhouse gas emissions and temperature changes under a baseline scenario



Source: PBL 2012

Future greenhouse gas emissions are mostly driven by an increase in energy use, while the relative contribution of land-use related emissions is projected to decrease.

CH_4 emissions from enteric fermentation and animal waste, and N_2O emissions from animal waste according to the IPCC method. This abatement is calculated in the IMAGE climate policy model FAIR (Section 8.1) by comparing the costs of non-CO_2 abatement in agriculture and other mitigation options.

3. Policy issues

Baseline developments

In a baseline scenario, most greenhouse gas emissions tend to increase, driven by an increase in underlying activity levels. This is shown in Figure 5.2.2 for a baseline scenario for the Rio+20 study (PBL, 2012). For air pollutants, the pattern also depends strongly on the assumptions on air pollution control. In most baseline scenarios, air pollutant emissions tend to decrease, or at least stabilise, in the coming decades as a result of more stringent environmental standards in high and middle income countries.

Policy interventions

Policy scenarios present several ways to influence emission of air pollutants (Braspenning Radu et al., in prep.):

- Introduction of climate policy, which leads to systemic changes in the energy system (less combustion) and thus, indirectly to reduced emissions of air pollutants (Van Vuuren et al., 2006).
- Policy interventions can be mimicked by introducing an alternative formulation of emission factors to the standard formulations (EKC, CLE). For instance, emission factors can be used to deliberately include maximum feasible reduction measures.
- Policies may influence emission levels for several sources, for instance, by reducing consumption of meat products. By improving the efficiency of fertiliser use, emissions of N_2O, NO and NH_3 can be decreased (Van Vuuren et al., 2011a). By increasing the amount of feed crops in the cattle rations, CH_4 emissions can be reduced. Production of crops has a significant influence on emission levels of N_2O, NO_x and NH_3 from spreading manure and fertilisers.
- Assumptions related to soil and nutrient management. The major factors are fertiliser type and mode of manure and fertiliser application. Some fertilisers cause higher emissions of N_2O and NH_3 than others. Incorporating manure into soil lowers emissions compared to broadcasting.

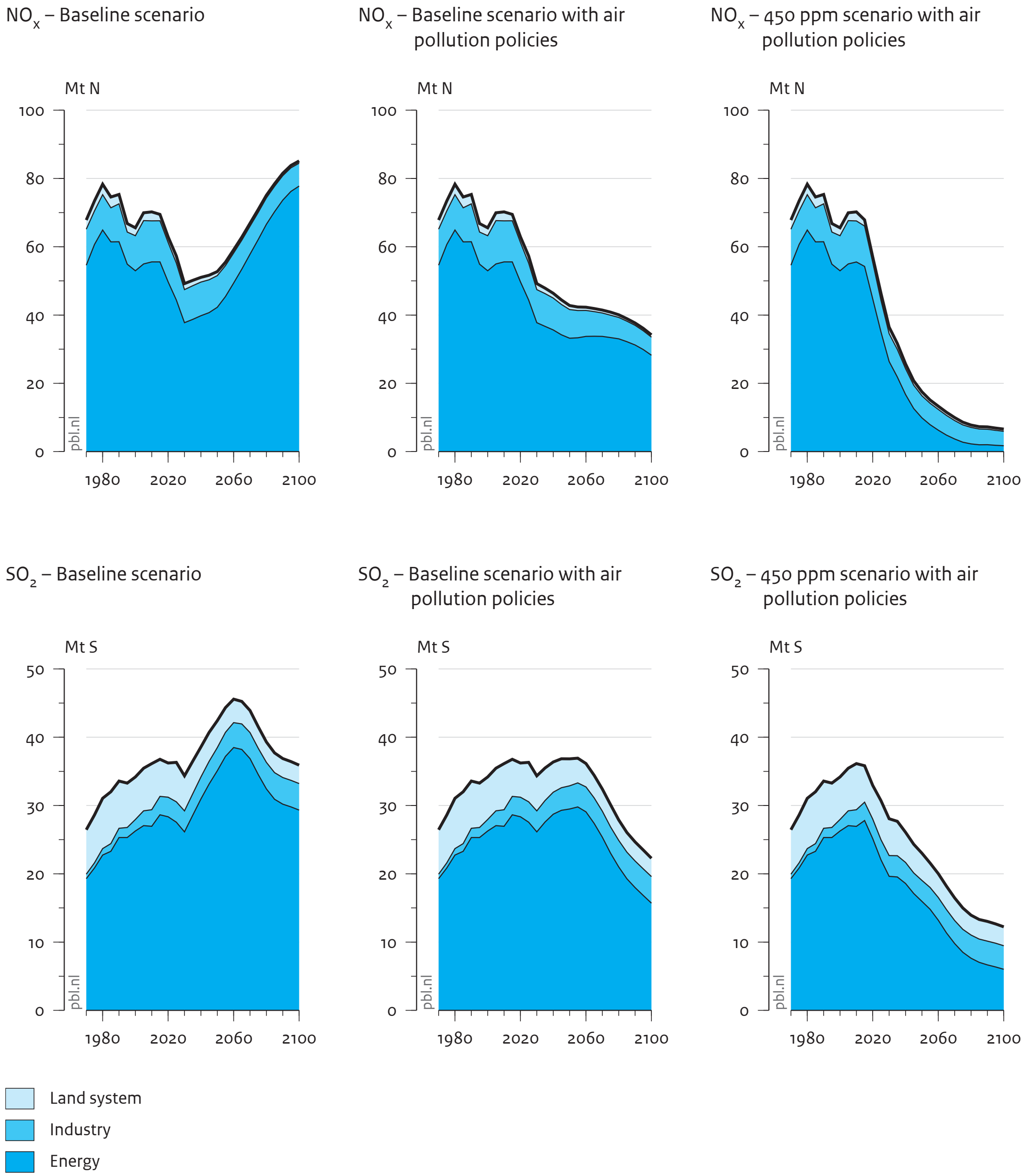
The impacts of more ambitious control policies (CLE versus EKC) on SO_2 and $NO_{x,}$ emissions, and the influence of climate policy are presented in Figure 5.2.3. Where climate policy is particularly effective in reducing SO_2 emissions, air pollution control policies are effective in reducing NO_x emissions.

4. Data, uncertainties and limitations

Data

Global emission data are provided in a range of inventories. The EDGAR database (JRC/PBL, 2012) was preferred for IMAGE because of its high level of detail and the similar sectoral and regional definitions. Alternative inventories include the database underlying the RAINS/GAINS system, the RETRO database and the RCP database (Lamarque et al., 2010). An overview of available inventories by Granier (2011) has shown large differences between the databases for carbon monoxide, nitrogen oxides, sulphur dioxide and black carbon on global and regional scales. Most emission factors for land-use emissions are based on IPCC methodologies and parameters (IPCC, 2006).

Figure 5.2.3
Global emissions of NO_x and SO_2 per sector under baseline and policy scenarios



Source: PBL 2014

Climate policy has important co-benefits for air pollution.

Uncertainties

EDGAR data on activities and emission factors need to be aggregated in order to be used in IMAGE. In this process, decisions need to be made (e.g., on the use of weighted averages and representative sectors), which lead to additional uncertainties. In general terms there are three levels of uncertainty. For energy and industry, emission factors for CO_2 are less uncertain than those for non-CO_2 emissions. In turn, the uncertainty in emission factors for land use and natural sources is larger than for energy and industry sources because of the extreme variability of the factors controlling processes in space and time.

Future emissions and their uncertainty depend on the activity levels determined by other IMAGE components, and on the emission factors. Estimations of future emission factors in the energy and industry systems, described above, rely on historical observations and learning curves. However, future legislation and effective implementation may influence these factors more, and more abruptly. Emission factors for land-use activities may change in the future, also in the absence of climate policy, but are assumed to be constant because of lack of data. As the future development of emission factors is per definition uncertain, the influence is explored by changing the emission factors for different storyline-based scenarios.

Limitations

IMAGE covers almost all emission sources and gases within a consistent framework, based on a few international data sets and authoritative sources. However, some specific emissions are only included as a group, without the underlying production processes. Even more importantly, IMAGE does not yet include emissions from peat and peat fires, although they constitute an important source of air pollutants and CO_2 emissions (IPCC, 2007a).

5. Key publications

Braspenning Radu O, Van Vuuren DP, van den Berg M, Klimont Z, Deetman S, Janssens-Maenhout G and Muntean M. (in prep.). Interactions between climate change and air pollution scenarios and the impact of climate policy on several air pollutants assumptions. *(available on request)*.

Van Vuuren DP, Bouwman L, Smith SJ and Dentener F. (2011a). Global projections for anthropogenic reactive nitrogen emissions to the atmosphere: an assessment of scenarios in the scientific literature. *Current Opinion in Environmental Sustainability* 3(5), DOI: 10.1016/j.cosust.2011.08.014.

Van Vuuren DP, Cofala J, Eerens HE, Oostenrijk R, Heyes C, Klimont Z, Den Elzen MGJ and Amann M. (2006). Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy* 34, pp. 444–460.

6. Input/Output Table

Table 5.2.1
Input in and output from the emission module

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	3
Energy and industry activity level	Activity levels in the energy and industrial sector, per process and energy carrier, for example, the combustion of petrol for transport or the production of crude oil.	4.1.1, 4.1.2, 4.1.3
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	4.2.4
Feed crop requirement	Crops required for feeding livestock.	4.2.4
Emission abatement	Reduction in emission factors as a function of Climate policy.	8.1
External datasets		
Emission factors	Exogenous emission factors per sector, activity and gas, mostly based on the EDGAR database.	JRC/PBL (2012)
Relationship income and emission factor	Relationship between GDP and emission factors.	-
Output	**Description**	**Use (section)**
CO_2 emission from energy and industry	CO_2 emission from energy and industry.	6.5, 8.1
Non-CO_2 GHG emissions (CH_4, N_2O and Halocarbons)	Non-CO_2 GHG emissions (CH_4, N_2O, Halocarbons).	6.5, 8.1
BC, OC and NO_x emissions	Emissions of BC, OC, SO_2 and NO_x per year.	6.5, 7.7, 8.1
CO and NMVOC emissions	Emissions from CO and NMVOC.	6.5, 8.1
SO_2 emissions	SO_2 emissions, per source (e.g. fossil fuel burning, deforestation).	6.5, 7.7, 8.1
Nitrogen deposition - grid	Deposition of nitrogen.	6.4, 7.2

EARTH SYSTEM

EARTH SYSTEM

6 Earth system

The Earth system in the IMAGE 3.0 model comprises the LPJmL model for carbon cycle, natural vegetation dynamics, agriculture, and hydrology (Box 6.1, Sections 6.1 – 6.3), a nutrient budget model (Section 6.4) and a climate model (Section 6.5).

Box 6.1: LPJmL, the carbon, vegetation, agricultural and hydrology model in IMAGE 3.0

Key policy issues

- What is the role of the terrestrial biosphere in the global carbon cycle, how will it change in time as a result of climate and land-use change?
- How do climate change and land-use management affect the productivity of current and future agricultural land?
- What is the combined effect of climate change and socio-economic development on water demand and availability, and associated agricultural production?

Within the Earth system, the terrestrial biosphere is the component that bears the most visible impact of human activity. Large proportions of the land surface and the terrestrial vegetation have been converted for human use, for instance, to cropland and urban areas.

Agriculture, terrestrial carbon, water and nutrient cycles were separate modules in previous versions of IMAGE and thus interactions were not adequately covered. IMAGE 3.0 covers natural and agricultural terrestrial ecosystems, and associated carbon and water dynamics via the link with the dynamic global vegetation, agriculture and water balance model LPJmL (Lund-Potsdam-Jena model with managed Land; Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007). This enables more detailed and process-based representation of the interacting dynamics in vegetation, carbon and agricultural production, and extends the model scope to terrestrial freshwater dynamics.

LPJmL is one of the most extensively evaluated dynamic global vegetation models (DGVM) and is widely applied either separately or linked to other models. To show the complex dynamics in the terrestrial biosphere, LPJmL is described in three sections: carbon cycle and vegetation (Section 6.1); agricultural land use (Section 6.2); and terrestrial freshwater flows (Section 6.3).

IMAGE 3.0 and LPJmL are linked through an interface that enables close and consistent interaction between the two models in annual time steps. An even more direct link to simulate detailed land-atmosphere interaction would require higher temporal resolutions also in other IMAGE components (e.g., the climate model), which is not necessarily congruent with the philosophy of an integrated assessment model. Incorporating nutrient cycles and improving representations of grassland management in LPJmL will require further adjustments to other IMAGE 3.0 components, and will increase consistency.

Key publications

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M and Smith B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13(3), pp. 679–706, DOI: 10.1111/j.1365-2486.2006.01305.x.

Gerten D, Schaphoff S, Haberlandt U, Lucht W and Sitch S. (2004). Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology* 286(1-4), pp. 249–270, DOI: 10.1016/j.jhydrol.2003.09.029.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K and Venevsky S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* 9(2), pp. 161–185, DOI: 10.1046/j.1365-2486.2003.00569.x.

6.1 Carbon cycle and natural vegetation

Christoph Müller, Elke Stehfest, Jelle van Minnen

Key policy issues

- What is the role of the terrestrial biosphere in the global carbon cycle and how will the terrestrial biosphere change as a result of climate and land-use change?
- To what extent can the terrestrial biosphere contribute to reducing the accumulation of CO_2 in the atmosphere and what are viable mechanisms?
- What are the contributions of land-use change, climate change and CO_2 fertilization on the future carbon cycle and how can these be considered in climate policies?

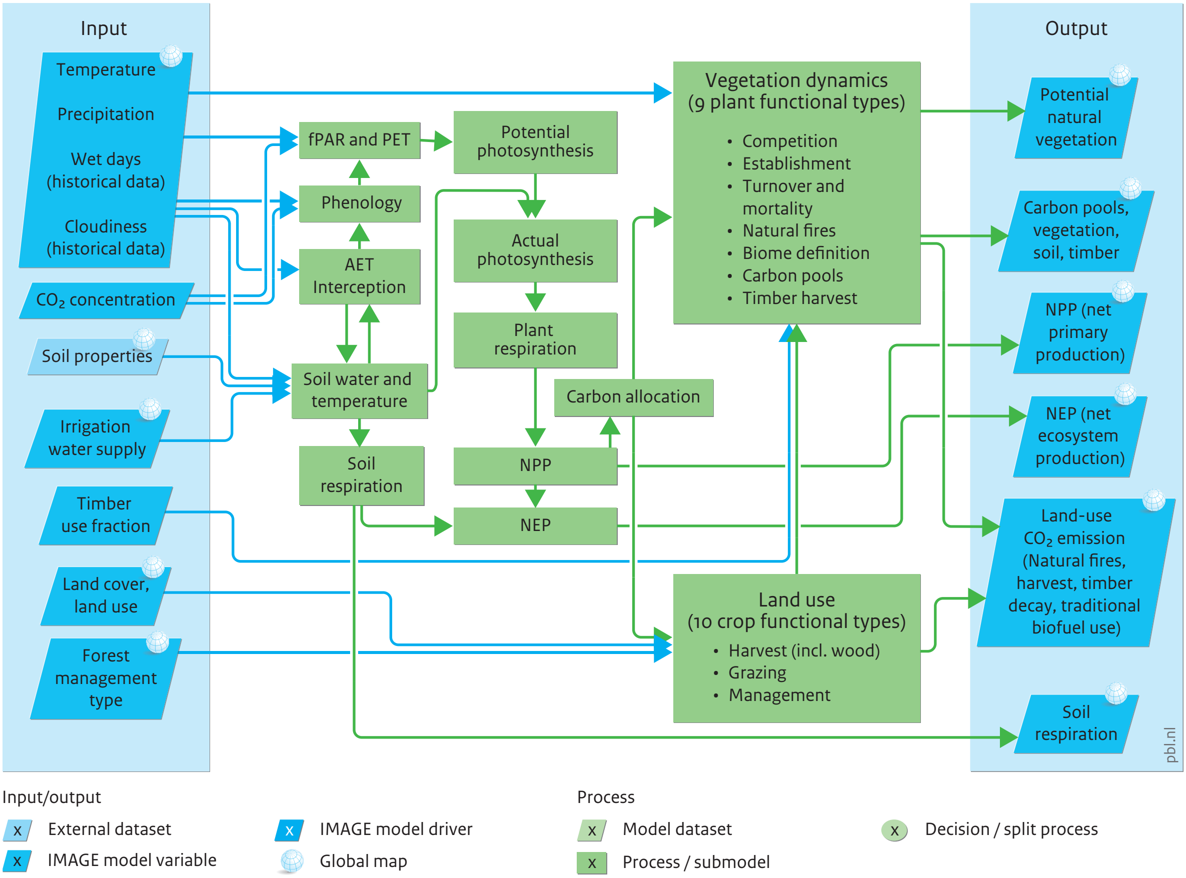
1. Introduction

The terrestrial biosphere plays a key role in global and regional carbon cycles and thus in the climate system. Large amounts of carbon (between 2000 and 3000 PgC) are stored in the vegetation and soil components. Currently, the terrestrial biosphere absorbs about 30% of emitted CO_2 (Ballantyne et al., 2012), and this carbon sink can be maintained and even enhanced by, for instance, protecting established forests and by establishing new forests (Van Minnen et al., 2008). However, deforestation and other land use changes in the last few centuries have contributed considerably to the build-up of atmospheric carbon dioxide (Van Minnen et al., 2009; Houghton, 2010) and this trend is projected to continue.

Regardless of land cover and land use, the net carbon sink in the terrestrial biosphere is affected by a range of environmental conditions such as climate, atmospheric CO_2 concentration and moisture. These conditions influence processes that take up and release CO_2 from the terrestrial biosphere such as photosynthesis, plant and soil respiration, transpiration, carbon allocation and turnover, and disturbances such as fires.

In plant photosynthesis, CO_2 is taken from the atmosphere and converted to organic carbon compounds. This CO_2 conversion is referred to as gross primary production (GPP). The sequestered carbon is needed for plant maintenance and growth (autotrophic respiration), and for the development of new plant tissues, forming live biomass carbon pools. All plant parts (including leaf fall and mortality) are ultimately

Figure 6.1.1
Carbon cylce and natural vegetation module of LPJmL, in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 6.1.1) stored as carbon in carbon pools in the soil and atmosphere. CO_2 is also emitted from the soil pools to the atmosphere in the process of mineralisation.

Terrestrial carbon cycle and vegetation models contribute to better understanding of the dynamics of the terrestrial biosphere in relation to these underlying processes and to the terrestrial water cycle (see Section 6.3) and land use (see Section 4.2).

The IMAGE-2 carbon cycle and biome model (Klein Goldewijk et al., 1994; Van Minnen et al., 2000) have been replaced by the Lund-Potsdam-Jena model with Managed Land (LPJmL) model (Sitch et al., 2003a; Gerten et al., 2004; Bondeau et al., 2007). An overview of the LPJmL model in the IMAGE context with regard to carbon and biome dynamics is presented here; the model and a sensitivity analysis is described in detail by Müller et al. (in prep.).

2. Model description

Vegetation types

LPJmL is a Dynamic Global Vegetation Model (DGVM) that was developed initially to assess the role of the terrestrial biosphere in the global carbon cycle (Prentice et al., 2007). DGVMs simulate vegetation distribution and dynamics, using the concept of multiple plant functional types (PFTs) differentiated according to their bioclimatic (e.g. temperature requirement), physiological, morphological, and phenological (e.g. growing season) attributes, and competition for resources (light and water).

To aggregate the vast diversity of plant species worldwide, with respect to major differences relevant to the carbon cycle, LPJmL distinguishes nine plant functional types (Figure 6.1.1). These include e.g. tropical evergreen trees, temperate deciduous broad-leaved trees and C3 herbaceous plants. Plant dynamics are computed for each PFT present in a grid cell. As IMAGE uses the concept of biomes, combinations of PFTs in an area/grid cell are translated into a biome type (see IMAGE website).

Carbon dynamics

IMAGE-LPJmL covers the carbon cycle processes, and tracks all carbon fluxes between the atmosphere and the biosphere. Carbon cycle dynamics of the terrestrial biosphere are computed as carbon uptake and release in plants (photosynthesis, autotrophic respiration), transfer of plant carbon to the soil (shedding of leaves, turnover, mortality) and mineralisation of soil organic matter (heterotrophic respiration; see Figure 6.1.1). Because these processes are closely related to weather conditions, they are computed in daily time steps.

The composition of natural vegetation depends on slower processes, such as the inter-annual and inter-seasonal variability in weather conditions and disturbances, such as natural fires. Thus, vegetation dynamics including competition between plant functional types, mortality, turnover, and fire disturbances are computed in annual time steps.

Allocation of newly established biomass is computed in annual time steps for perennial plants (natural grasses, trees) and in daily time steps for annual plants (crops). Allocation to plant organs (represented by a carbon pool for each) distinguishes up to four living plant carbon pools, depending on plant type. For grasses, the model distinguishes carbon pools of leaves and roots only, and for trees, there are two additional woody carbon pools (hardwood and sapwood). For agricultural crops, the pools are categorised as leaves, roots, storage organs, stems, and a mobile reserve pool.

To simulate mineralisation rates of soil organic carbon, the model distinguishes three soil carbon pools for litter, fast soil organic matter (10-year turnover rate) and slow soil organic matter (100-year turnover rate). All carbon from harvested products (crops, grass, biofuels) is assumed to be released to the atmosphere as CO_2 after consumption (food, feed, energy) in the same year. Residues are either left in the fields to enter the litter pool or are removed to subsequently decompose.

During wood harvesting, a proportion of the plant pools is cut down and harvested, as determined in the forest management model (Section 4.2.2). The waste is left to enter the soil litter pool as dead biomass. Three classes of wood products are distinguished to account for differences in lifespan: pulp and paper has fast turnover rates; timber products, such as furniture, have longer turnover rates (Lauk et al., 2012); and traditional biomass used as an energy source is emitted as CO_2 within the same year.

The IMAGE land-use components (Sections 4.2 and 5.1) determine annual land-use dynamics, including expansion or abandonment of pastures, cropland and bioenergy plantations, and wood harvested from natural vegetation.

Model linkage and simulation procedure

The LPJmL model has multiple links to other IMAGE components and uses IMAGE data on climate, atmospheric CO_2 concentration, land use (including wood demand), and timber use and deforestation (cutting and burning). LPJmL supplies other IMAGE components with information on annual carbon fluxes, net CO_2 exchange between biosphere and atmosphere, size of carbon pools, and biome classes.

LPJmL and IMAGE are linked via an interface and simulations with annual data exchange starts in the simulation year of 1970. Before 1970, vegetation and soil carbon pools need to be initialised. This is done by using LPJmL first in a 1000-year spin up to initialise the natural ecosystems and their carbon pools and fluxes, followed by a 390-year spin up, in which agricultural land is gradually expanded based on historical HYDE land-use data

(Klein Goldewijk et al., 2011). The pool sizes of timber products for 1970 are based on literature estimates (Lauk et al., 2012).

The linked IMAGE-LPJmL simulations start in 1970 with observed climate, followed by simulated climate from 2005 onwards (Section 6.5). As the inter-annual variability in weather conditions is needed for the simulation of vegetation dynamics in IMAGE-LPJmL, smooth annual climate trends from IMAGE are superimposed with inter-annual variability fields, extracted from observed climate over the 1971–2000 period. To avoid repeating climate trends in these 30-year periods, annual anomalies are ordered at random before superimposition.

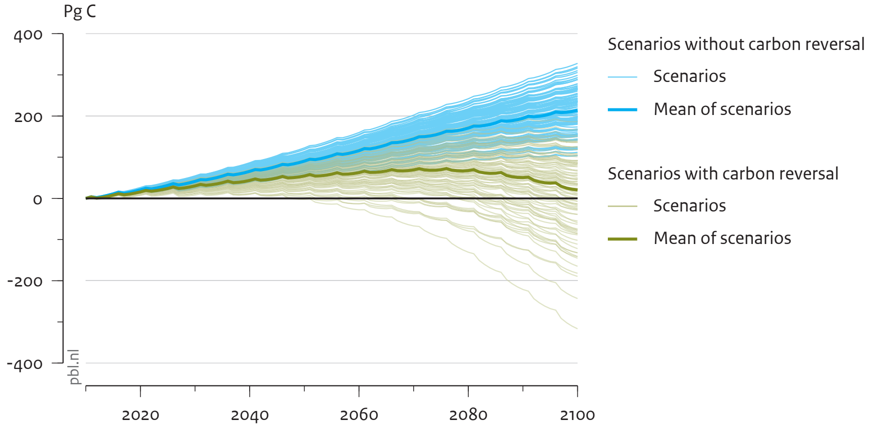
3. Policy issues

Baseline developments
Several economic developments and policy interventions are related to the dynamics of the terrestrial carbon budget. The terrestrial and marine carbon budgets determine the overall reduction in greenhouse gas emissions and aerosols needed to limit CO_2 build-up in the atmosphere. If the current terrestrial sink diminishes or becomes a carbon source, additional emission reductions will be required. Furthermore, protecting natural ecosystems or using alternative forest management options may contribute to storing and retaining more carbon in the biosphere (see also Strengers et al., 2008; Van Minnen et al., 2008). These options can be evaluated with the linked IMAGE-LPJmL model for baseline scenarios and policy interventions.

For instance, the IMAGE-LPJmL model has been used to assess key uncertainties about the terrestrial carbon balance (Figure 6.1.2). The study conducted by Müller et al. (in prep.) included multiple values for climate sensitivity, including multiple climate patterns, for two different socio-economic scenarios. These experiments showed a possible shift in the terrestrial biosphere from sink to source under a broad range of changes in mean global temperature (2.3-6.8 °C up until 2100), and atmospheric CO_2 concentrations (475–936 ppm). The rate of temperature increase was identified as the decisive threshold determining the shift, with values from 0.04 to 0.08 °C/y, depending on the GCM pattern. The LPJmL model calculations suggest that the likelihood of a carbon balance shift in the 21st century increases almost linearly from ~5% to ~90% when climate sensitivity is increased from 2.5°C to 5.0 °C.

Policy interventions
The model can also be used to study the impact of a range of policy measures, for example aimed at increasing the carbon storage of natural vegetation. Policy measures to increase carbon storage often generate co-benefits, such as restoration of watershed and wildlife habitats, and prevention of soil erosion. However, a critical issue is the permanency of additional carbon storage.

Figure 6.1.2
Cumulative terrestrial carbon flux of long-term climate scenarios



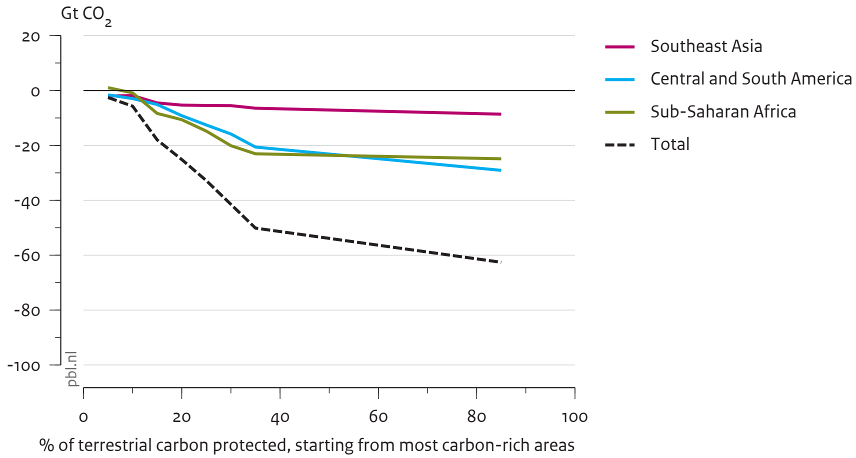
Source: Müller et al. in preparation

Positive numbers depict a cumulative terrestrial carbon sink, negative numbers a cumulative terrestrial source (net carbon release exceeds the amount of carbon sequestered before). Although the terrestrial biosphere has always been a carbon sink, it may become a carbon source in the future (Müller et al., in prep.).

For instance, a policy intervention would be the use of forestry measures allowed under the Kyoto Protocol. The protocol provides opportunities for developed countries to partly achieve their emission reduction targets by planting new forests or by managing established forests and agricultural land to store more carbon in the soil (ARD), and to reduce emissions resulting from deforestation and degradation (REDD). Recently, IMAGE was used to estimate the emission reductions and costs related to REDD schemes (Overmars et al., accepted). Forest carbon stocks are protected from agricultural expansion at increasingly high levels, and not available for agricultural use in MAGNET and IMAGE. As a result, agriculture expands less, and CO_2 emissions are reduced by up to 100 Gt CO_2 compared to baseline levels, with most of the reduction potential in Latin America and Africa (Figure 6.1.3).

Figure 6.1.3

Change in cumulative CO_2 emissions under increasing forest protection, compared to the baseline scenario, 2010 – 2030



Source: Overmars et al. accepted

Increasingly strict REDD regimes might lead to substantial reduction in cumulative terrestrial CO_2 emission (Overmars et al., accepted).

4. Data, uncertainties and limitations

Data

The LPJmL model uses the FAO harmonised world soil map, to provide information on soil texture and hydraulic properties (FAO et al., 2009). Climate input data come from the IMAGE climate model. Comparison of carbon stocks and fluxes with IPCC estimates shows these estimates are well within the uncertainty range. The modelled distribution of plant functional types has been found to compare well to other data sources.

Uncertainties

Although the terrestrial biosphere plays a key role in the global carbon cycle, it is also subject to considerable uncertainty. Current carbon fluxes are highly uncertain because they cannot be observed directly on a large scale, and vary considerably in time and space. Thus, all available estimates of global carbon pools and fluxes are model-based.

For the future dynamics of the terrestrial carbon cycle, additional uncertainty arises from physiological and ecological processes and interactions, which change rapidly under changing environmental conditions. As a dynamic global vegetation model, LPJmL can simulate carbon dynamics under internally computed vegetation shifts that occur in response to climate change, the impacts of land-use change, water availability and CO_2 fertilisation (Heyder et al., 2011). The most uncertain parameters in future dynamics are the combined effect of temperature and precipitation change on soil respiration, and the effect of CO_2 fertilisation. An uncertainty range for how the terrestrial biosphere may react to climate change scenarios is presented above.

Limitations

Permafrost modules have recently been developed to improve assessment of future climate change impacts on the carbon balance (Schaphoff et al., 2013), but as yet have not been included in IMAGE-LPJmL. Impacts of weather extremes can be assessed, provided they are represented in the climate input data (e.g., heat waves, dry spells). However, only few data are available on the effects of weather extremes on the carbon balance to enable evaluation of the model's capability in this respect. Simulation results from LPJmL calculation are within current estimates (Vetter et al., 2008).

Another limitation of the LPJmL model is that as yet it does not include nutrients, although nitrogen is assumed to modify the reaction of crops and natural vegetation to elevated CO_2 concentration levels and climate change.

5. Key publications

Müller C, Stehfest E, van Minnen JG, Strengers B, von Bloh W, Beusen A, Schaphoff S, Kram T and Lucht W. (in prep.). Reversal of the land biosphere carbon balance under climate and land-use change., *(available on request)*.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K and Venevsky S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* 9(2), pp. 161–185, DOI: 10.1046/j.1365-2486.2003.00569.x.

6. Input/Output Table

Table 6.1.1

Input in and output from the carbon cycle and natural vegetation module of LPJmL

Input	Description	Source (section/other)
IMAGE model drivers and variables		
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
Cloudiness - grid	Percentage of cloudiness per month; assumed constant after the historical period.	6.5

Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period.	6.5
CO_2 concentration	Atmospheric CO_2 concentration.	6.5
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Irrigation water supply - grid	Water supplied to irrigated fields; equal to irrigation water withdrawal minus water lost during transport, depending on the conveyance efficiency.	6.3
Forest management type - grid	Forest management type: clear cut, selective logging, forest plantation or additional deforestation.	4.2.2
Timber use fraction	Fractions of harvested timber entering the fast-decaying timber pool, the slow-decaying timber pool, or burnt as traditional biofuels.	4.2.2
External datasets		
Soil properties - grid	Soil types and soil properties, such as soil texture, soil depth and water holding capacity.	HWSD database (FAO et al., 2009)
Output	**Description**	**Use (section)**
Potential natural vegetation - grid	Potential natural vegetation type/biome, based on distribution of plant functional types.	5.1
Carbon pools in vegetation - grid	Carbon pools in leaves, stems, branches and roots).	4.2.2, 5.1
Carbon pools in soil and timber - grid	Carbon biomass in three soil pools (litter, humus and charcoal) and two timber pools (slow decaying, and fast decaying).	5.1
Land-use CO_2 emissions - grid	Land-use CO_2 emissions from deforestation, wood harvest, agricultural harvest, bioenergy plantations and timber decay.	6.5, 8.1
NEP (net ecosystem production) - grid	Net natural exchange of CO_2 between biosphere and atmosphere (NPP minus soil respiration), excluding human induced fluxes such as emissions due to deforestation and decay of wood products.	6.5, 7.6
NPP (net primary production) - grid	CO_2 sequestered by plants and incorporated in new tissue in plant carbon pools.	5.1
Soil respiration - grid	CO_2 release from soils into the atmosphere due to the decay of soil carbon pools and respiration of soil organisms.	Final output

6.2 Crops and grass

Christoph Müller and Elke Stehfest

Key policy issues:

- How will climate change affect the productivity of current and future agricultural areas?
- How could management improve agricultural productivity under current and future water constraints?
- How will agriculture affect the Earth system with respect to carbon emissions, freshwater availability and nutrient cycles?

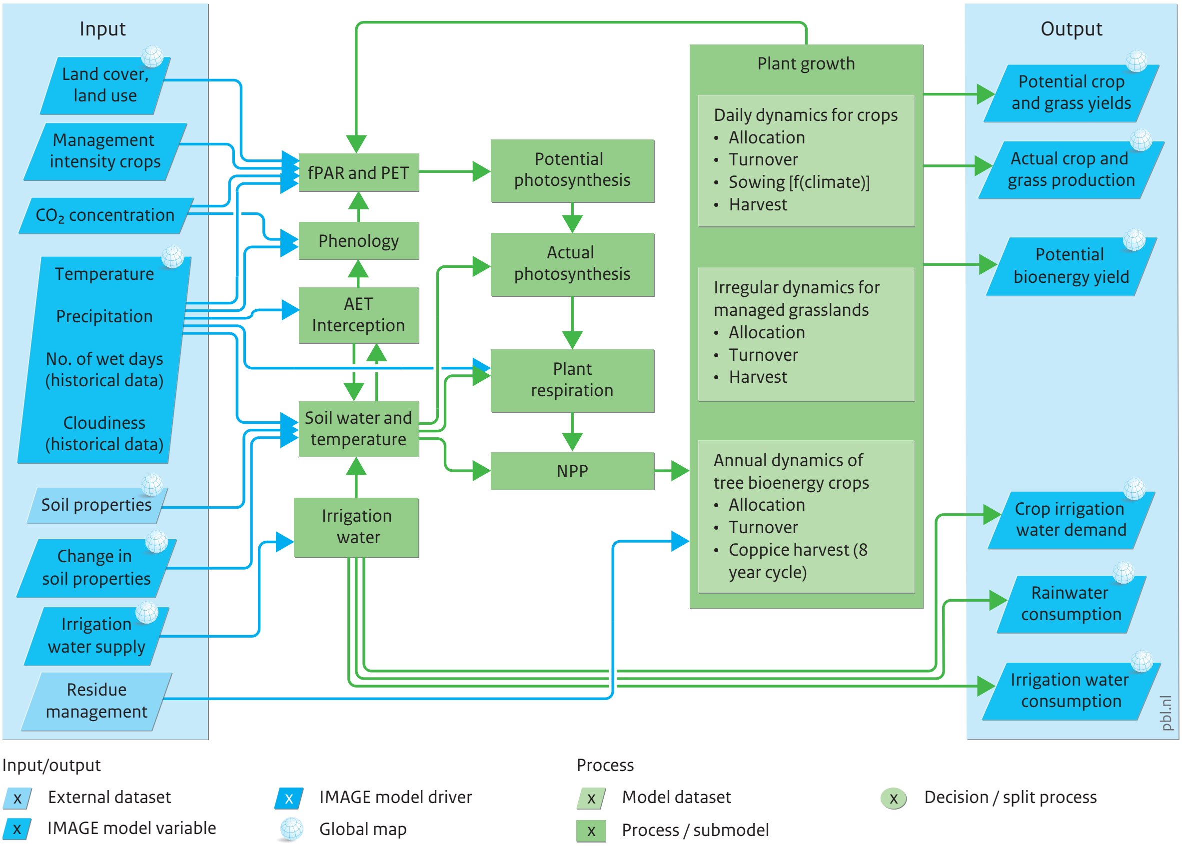
1. Introduction

World population and per capita consumption of agricultural products are projected to increase substantially, which will require a significant increase in agricultural production. Currently, over one third of the Earth's land area is under agricultural production, which is already about half the area suitable for agriculture. Pasture covers 68% of the global agricultural area, and cropland covers 32%. Agricultural production can be increased by expanding the agricultural area (more hectares) and by intensification (higher output per hectare).

However, the extent and distribution of agricultural land affects the Earth system, because agricultural systems are closely linked with natural ecosystems, human societies and the climate system. Agricultural land differs significantly from natural ecosystems in biogeochemical (e.g., carbon, water, nutrients) and bio-geophysical (e.g., albedo, energy balance) properties. Current land-use patterns have a significant impact on climate (Pitman et al., 2009; Strengers et al., 2010), and climate directly affects agricultural productivity (Müller et al., 2009; Rosenzweig et al., 2013). A large proportion of anthropogenic greenhouse gas emissions is caused by agricultural production, mediated by management and associated land-use dynamics (IPCC, 2007b).

Crop growth models are used to assess future area requirements, spatial patterns of agricultural production, and available areas for biomass-based energy (bioenergy). IMAGE 3.0 uses the LPJmL model on dynamic global vegetation, agriculture and hydrology (Bondeau et al., 2007; Fader et al., 2010; Waha et al., 2012). This model dynamically simulates plant growth, agricultural productivity, and the carbon and water dynamics of agricultural land with detailed processes of photosynthesis, respiration, growth and phenology. In the model's current form, management intensity can be approximated per crop type on national scale (Fader et al., 2010). Irrigation patterns are

Figure 6.2.1
Crop and grass module of LPJmL, in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 6.2.1).

obtained from the Land-use allocation model of IMAGE (Section 4.2.3), and other management options are calculated internally, such as sowing dates, selection of crop varieties and the demand for irrigation water.

LPJmL simulates yields per crop under optimal management intensities for each grid cell and irrigation system as well as irrigation water requirements, which is input to the IMAGE Land-use allocation model (Section 4.2.3) for simulations of land-use change dynamics. Climate change calculated by the IMAGE climate model (Section 6.5) directly affects future agricultural productivity because these components are dynamically linked in annual time-steps.

2. Model description

The LPJmL model is a global dynamic vegetation, agriculture and water balance model. The agriculture modules are intrinsically linked to natural vegetation via the carbon and water cycles and follow the same basic process-based modelling approaches, plus additional process representation (management) where needed.

Crop productivity is computed following the same representation of photosynthesis, maintenance and growth respiration as for natural vegetation (see Figure 6.1.1), but with additional mechanisms for phenological development, allocation of photosynthesis to crop components (leaves, roots, storage organ, mobile pool/stem), and management (Figure 6.2.1), which can greatly affect crop productivity and food supply.

In aggregating plant species to classes, the 12 crops currently implemented in LPJmL (Bondeau et al., 2007; Lapola et al., 2009) represent a broader group of crops, referred to as crop functional types (see Table 6.2.2). Currently, LPJmL has only a crude representation of managed grasslands and further development will take account of different management systems. These changes will be implemented in the IMAGE-LPJmL model as soon as available.

For the cultivation of bioenergy plants, such as short-rotation tree plantations and switch grass, three additional functional types have been introduced: temperate short-rotation coppice trees (e.g., willow); tropical short-rotation coppice trees (e.g., eucalyptus); and *Miscanthus* (Beringer et al., 2011).

Climate-related management is included in the model endogenously to take account of smart farmer behaviour in long-term simulations. Sowing dates are calculated as a function of farmers' climate experience (Waha et al., 2012), and also selection of crop varieties (Bondeau et al., 2007).

Table 6.2.2
Crop types in LPJmL and functional crop groups

Crops in LPJmL	Crops represented
Wheat (spring/winter)	Temperate cereals (wheat, rye, oats, barley, triticale)
Rice	Rice
Maize	Maize
Millet	Tropical cereals (millet, sorghum)
Field peas	Pulses
Sugar beet	Temperate roots and tubers
Cassava	Tropical roots and tubers
Sunflower	Sunflower
Soybean	Soybean
Groundnut	Groundnut
Rapeseed	Rapeseed
Sugar cane	Sugar cane

Individual crops and grass are assumed to be cultivated on separate fields, and thus simulated with separate water balances, but soil properties are averaged in fallow periods to account for crop rotations. All crops in one grid cell are simulated in parallel, both irrigated and non-irrigated crops.

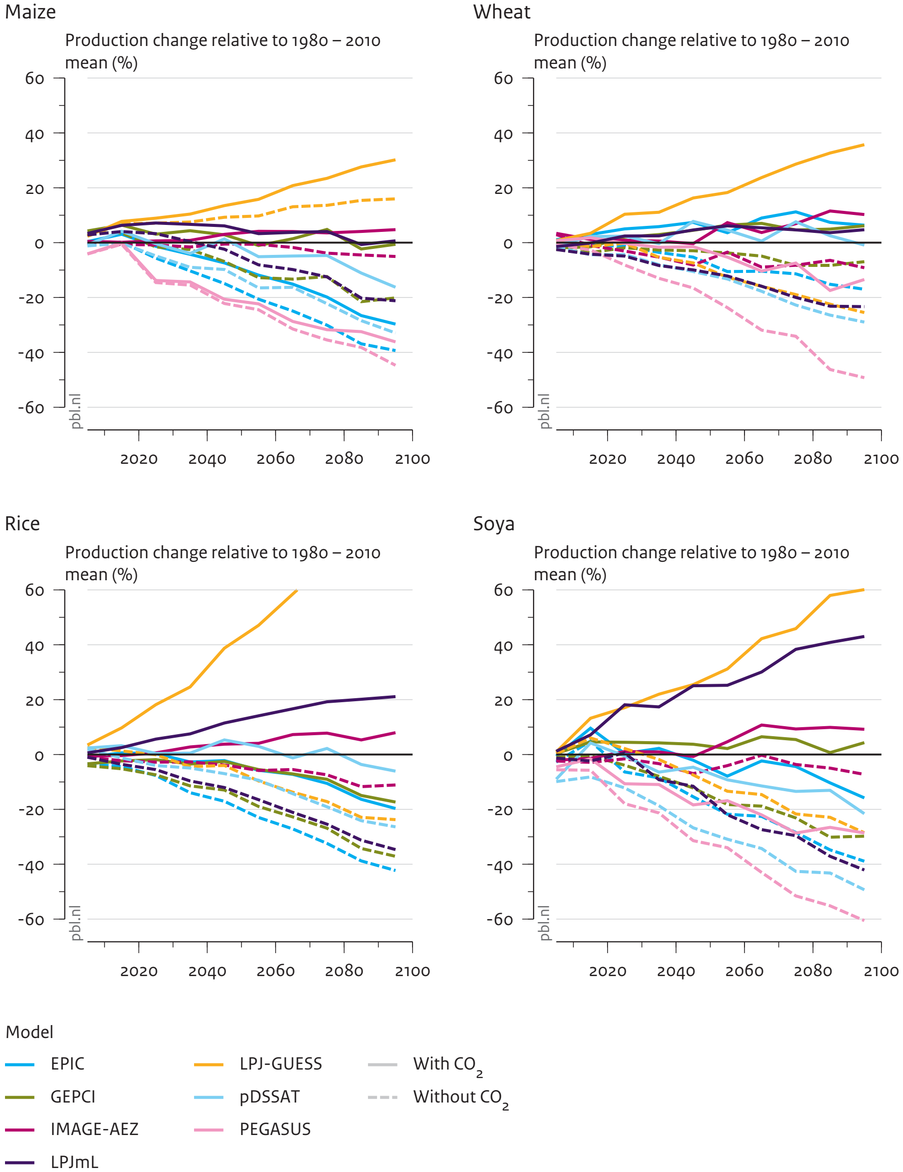
Irrigation modules are constrained by available water from surface water bodies and reservoirs (see Section 6.3), or assume unconstrained availability of irrigation water (scenario setting) to account for prevalent use of (fossil) groundwater.

To compensate for no explicit representation of nutrient cycles and other management options that may affect productivity (e.g., pest control, soil preparation), LPJmL can account for management intensity levels, and can be calibrated to reproduce actual FAO yields (Fader et al., 2010). However, given the complex interaction with the Land-use allocation model (Section 4.2.3), LPJmL simulates crop yields without nutrient constraints (potential water-limited yields) in the link with IMAGE. Actual yields are derived by IMAGE by combining potential yields from LPJmL with a management factor that can change over time (see Section 4.2.1). As input for the IMAGE land-use components (Section 4.2), LPJmL calculates productivity of each crop in each grid cell under rain-fed and irrigated conditions.

The crop and grassland component is embedded in the dynamic global vegetation, agriculture and water balance model LPJmL, and thus carbon and water dynamics (Sections 6.1 and 6.3, respectively) consistently account for dynamics in agricultural productivity and land-use change.

Figure 6.2.2

Relative change in decadal mean production according to the GGC models, with and without CO_2 fertilization effect



Source: Rosenzweig et al. 2013

The effect of climate change on crop yields strongly depends on the effect of CO_2 fertilisation, also represented in LPJmL. Lines show means across several climate scenarios.

3. Policy issues

Baseline developments

Climate change significantly affects crop yields, and these effects differ considerably per region and crop. Assumptions on CO_2 fertilisation strongly influence the climate change effect. Without CO_2 fertilisation, global average crop yields decline under changing climate but increase for most crops under standard assumptions on CO_2 fertilisation (Figure 6.2.2).

Policy interventions

Policy interventions that directly affect agricultural production systems comprise environmental regulation, such as use of fertilisers and pesticides. These interventions cannot be directly assessed by the model because of lack of explicit nutrient dynamics, no direct coverage of pest control and water quality. Instead, the model evaluates several indirect policy interventions, such as impacts of climate policy, dietary habits, trade patterns, and land-use regulation.

Climate policies focus on atmospheric CO_2 concentration levels, and affect the degree of global warming, and shifts in precipitation patterns. These factors have an impact on agricultural productivity and thus indirectly also influence land-use patterns and water requirements. The impact of climate change on agricultural productivity results from several interacting mechanisms. For instance, climate change and the associated increase in atmospheric CO_2 concentrations may increase yields in temperate regions (see Figure 6.2.3) but decrease agricultural productivity in subtropical and tropical regions. As a consequence, agriculture is abandoned in some areas and expanded to other regions. If policy interventions lead to large reductions in greenhouse gas emissions, this directly affects agricultural productivity and associated land-use dynamics (Figure 6.2.3).

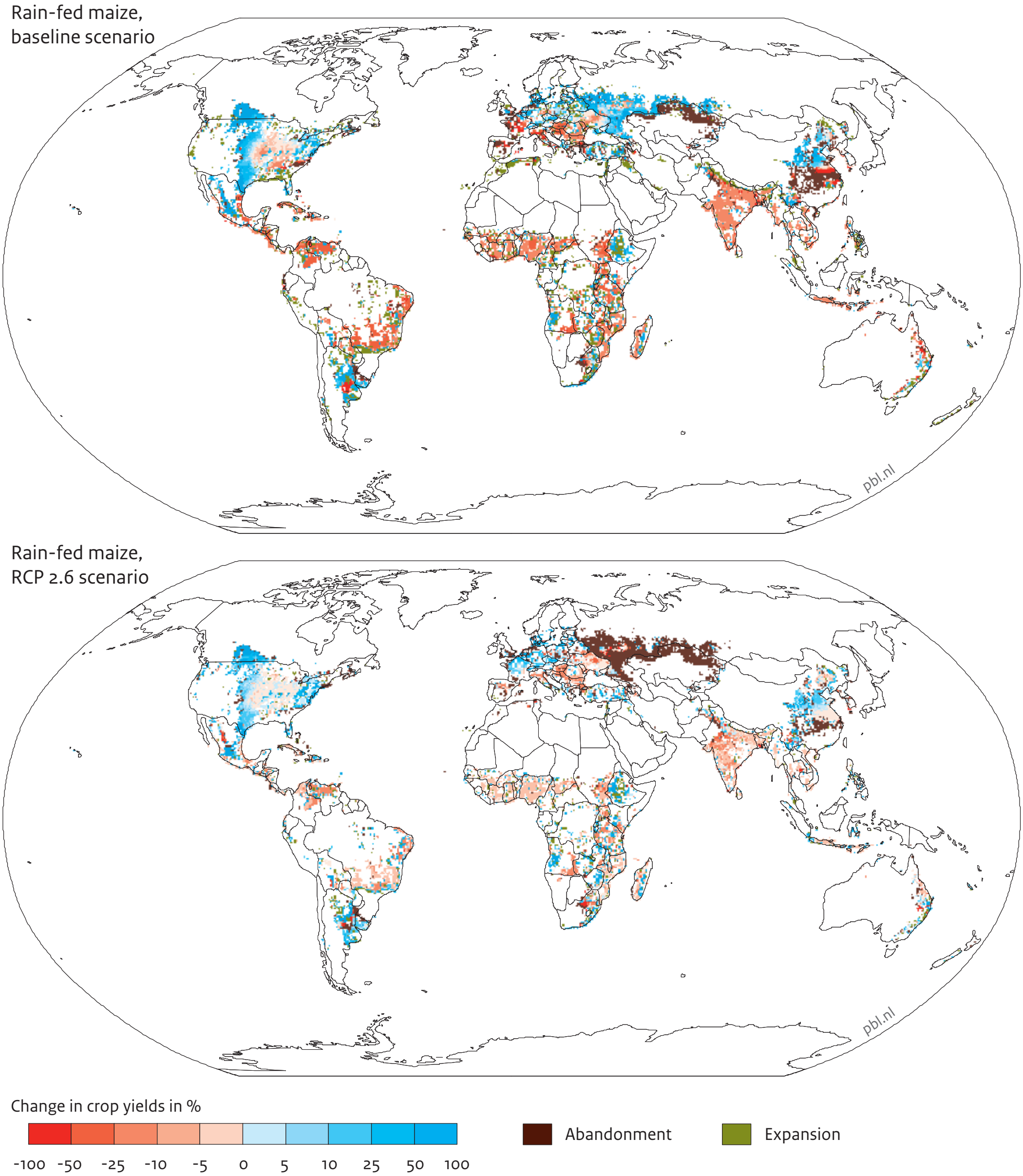
4. Data, uncertainties and limitations

Uncertainties

Crop model simulations are subject to considerable uncertainties with respect to model implementations and process representation, and thus vary significantly at field and global scale. On a global scale, detailed data are often not available on basic management options, such as sowing dates and variety selection. Global simulations do not represent actual crop production systems, but at best represent plausible production systems.

Even though there may be significant differences in susceptibility to climate change, simulations of plausible cropping systems with global coverage are the best available indications of climate change impacts on actual cropping systems.

Figure 6.2.3
Climate change impacts on crop yields from 1981 – 2010 to 2070 – 2099



Source: PBL 2014

By the end of the century climate change impacts on crop yields under the baseline could be reduced by stringent climate policy.

A major uncertainty in climate change projections is the effectiveness of CO_2 fertilisation on crop yields. Crop growth is stimulated under elevated atmospheric CO_2 concentrations for many crops (C3 photosynthesis, such as wheat and rice) and water-use efficiency improves for all crops. However, the translation of higher photosynthesis to higher yields is less clear and subject to interacting processes, such as photosynthetic downregulation, increased nutrient limitation, and increased susceptibility to insect damage.

LPJmL has been shown to be capable of reproducing agricultural water and carbon fluxes and pools for several sites (Bondeau et al., 2007). However, projections of global yield patterns are difficult to evaluate because of the strong management signal that is currently not represented at the process base in the model.

Initial results from comparison of the global gridded crop models (joint activity of the Agricultural Model Inter-comparison and Improvement Project (ww.AgMIP.org) and the Inter-Sectoral Impact Model Inter-comparison (www.ISI-MIP.org)) indicate that LPJmL results are within the range of other model projections, but are on the optimistic end for effectiveness of CO_2 fertilisation (Rosenzweig et al., 2013, and Figure 6.2.2).

Limitations

A major limitation of LPJmL and most other global gridded crop models is poor representation of extreme weather events and the effects on crop productivity. The occurrence of such extreme events is uncertain in climate change projections and the effect on crop productivity is not well understood. An increase in precipitation intensity or hail during the cropping season could devastate crop yields. Extreme temperatures may have similar effects if they occur during sensitive phenological stages, such as flowering.

Similar to most other crop models, LPJmL does not address the impacts of an altered frequency in short-term extreme weather events, such as brief but heavy precipitation. Addressing these impacts is prohibited by the temporal resolution of the model (daily) and input data (monthly interpolated to daily). The effects of periods of heat and drought could be addressed because a daily time step is sufficient but the model's performance has not been assessed in this respect and the climate model in IMAGE currently does not account for extreme weather events (Section 6.5). From the perspective of weather extremes, all crop model projections must be considered to be on the optimistic side.

Land-use data from IMAGE available on a 5 minute spatial resolution are aggregated to the 30 minute resolution of LPJmL. Higher spatial resolution in the simulation of agricultural productivity would allow for more flexibility in land-use allocation, but is currently prohibited by computational requirements and the resolution of the river routing scheme in the hydrology module (section 6.3).

5. Key publications

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M and Smith B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13(3), pp. 679–706, DOI: 10.1111/j.1365-2486.2006.01305.x.

Waha K, van Bussel LGJ, Müller C and Bondeau A. (2012). Climate-driven simulation of global crop sowing dates. *Global Ecology and Biogeography* 21(2), pp. 247–259, DOI: 10.1111/j.1466-8238.2011.00678.x

6. Input/Output Table

The LPJmL module on crop growth directly interacts with the modules on terrestrial carbon (Section 6.1), water cycles (Section 6.3); as they are all an integral part of the LPJmL model, sharing the same soil and water balance processes, the distinction in different modules is somewhat artificial.

Table 6.2.1
Input in and output from the crop and grass module of LPJmL

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
Cloudiness - grid	Percentage of cloudiness per month; assumed constant after the historical period.	6.5
Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period.	6.5
CO_2 concentration	Atmospheric CO_2 concentration.	6.5
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Management intensity crops	Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions – current practice and technological change in agriculture – and is endogenously adapted in the agro-economic model.	4.2.1
Irrigation water supply - grid	Water supplied to irrigated fields; equal to irrigation water withdrawal minus water lost during transport, depending on the conveyance efficiency.	6.3

Change in soil properties - grid	Change in soil properties, such as clay/sand content, organic carbon content, soil depth (topsoil/subsoil).	7.5
External datasets		
Residue management	Assumptions on residue management in agriculture.	–
Soil properties - grid	Soil types and soil properties, such as soil texture, soil depth and water holding capacity.	HWSD database (FAO et al., 2009)
Output	**Description**	**Use (section)**
Actual crop and grass production - grid	Actual crop and grass production on agricultural land, based on potential yield and management intensity	6.4
Potential crop and grass yield - grid	Potential crop and grass yield, changing with time due to climate change and possibly soil degradation.	4.2.1, 4.2.3
Potential bioenergy yield - grid	Potential yields of bioenergy crops.	4.1.3, 4.2.3
Crop irrigation water demand - grid	Water requirements for crop irrigation, calculated as daily moisture deficit during the growing season.	6.3
Rainwater consumption - grid	Rain water consumption by crops.	Final output
Irrigation water consumption - grid	Irrigation water consumption by crops.	Final output

6.3 Water

Hester Biemans, Dieter Gerten, Elke Stehfest, David Beijl, Tom Kram

Key policy issues

- What is the combined effect of climate change and socio-economic development on water demand and availability, and on associated agricultural production?
- What is the potential of adaptation measures to reduce water stress and water-related crop production losses?
- How can water demand be reduced and still provide the adequate service levels to the sectors with the highest demand?

1. Introduction

Water availability is essential for natural vegetation and agricultural production, human settlements and industry. Around one third of the world's population lives in countries suffering from medium to high water stress (OECD, 2012). This number is expected to increase as water demand will increase due to population growth, and as water availability may decrease due to global warming.

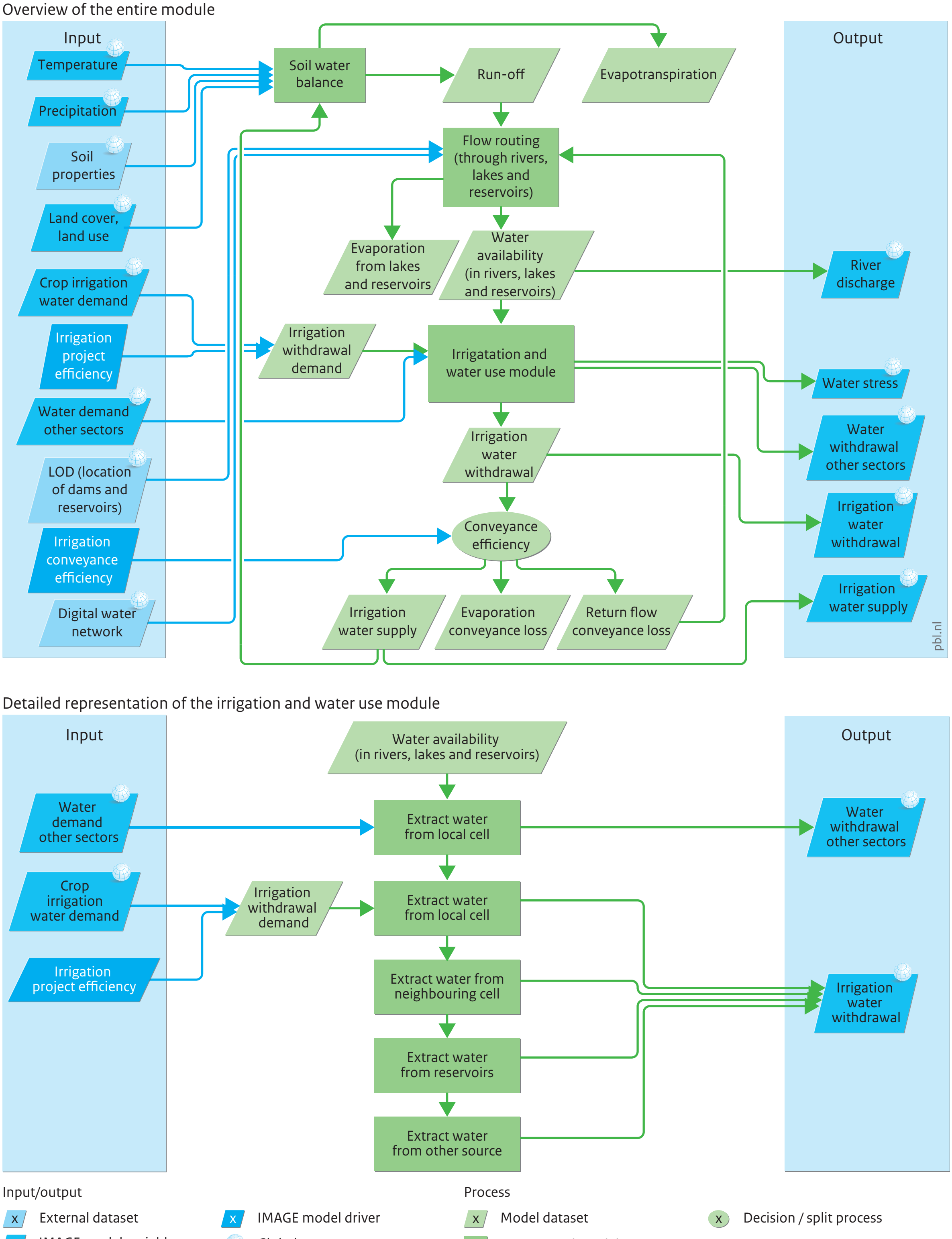
Today, agriculture accounts for 70% of the total global water withdrawals. Around one third of the total global crop production is irrigated although only occupying 17% of croplands (e.g. Portmann et al., 2010). Irrigated agriculture is expected to increase further to meet the growing demand for food (Fischer et al., 2005; Molden, 2007; FAO, 2011). Moreover, water demand in other sectors (domestic, electricity, manufacturing) is projected to increase substantially in the coming decades (OECD, 2012). As a result, competition between water uses will increase and the resulting water shortages may affect future food production.

Although the global total quantity of freshwater is more than sufficient to meet all human needs, uneven distribution makes water a scarce resource in some regions and watersheds. Furthermore, climate change will lead to changes in precipitation patterns, thus altering future water availability and adding to water stress in areas where precipitation levels are expected to decline.

To identify current and future areas of water stress, IMAGE includes a hydrology model that calculates water availability and demand. The hydrological module of LPJmL is fully integrated with the terrestrial carbon and land-use dynamics of LPJmL and the rest of IMAGE and dynamically calculates agricultural water demand as well as water

Figure 6.3.1

Water module of LPJmL, in IMAGE 3.0



More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 6.3.1).

availability and withdrawals. Availability of renewable water is the net result of precipitation, interception loss and evapotranspiration by plants and soils. In the model, the surplus in each grid cell flows to neighbouring grid cells in a watershed by means of a river routing scheme. However, river flows are modified by dams and reservoirs used for irrigation, or hydropower production, or both.

The effects of water stress on crop production can be quantified, and by including the feedback of water-limited crop production on land allocation, IMAGE can produce more realistic scenarios for cropland expansion and agricultural intensification. IMAGE and LPJmL are fully and dynamically linked (see Box 6.1), and thus IMAGE scenarios include an integrated assessment of the water cycle, and can be used to assess water availability and demand at high spatial (0.5x0.5 degree grid cells) and daily resolutions.

2. Model description

In IMAGE, the hydrological cycle is represented by LPJmL (Sitch et al., 2003a; Bondeau et al., 2007; Gerten et al., 2013), which simulates the global hydrological cycle as part of the dynamics of natural vegetation and agricultural production systems. Because LPJmL is linked to IMAGE, there is consistency in the way the carbon cycle, natural vegetation dynamics (Section 6.1), crop growth and production (Section 6.2), land-use allocation (Section 4.2.3) and the water balance can be modelled.

Data on annual land cover and land use (Section 5.1) are used as input to LPJmL, including information on the location of irrigated areas and crop types (Figure 6.3.1 and Table 6.3.1). This affects the amount of water that evaporates and runs off, as well as the amount of water needed for irrigated areas during the (simulated) growing season of crops. Similarly, information on water availability calculated by LPJmL is taken into account in the Land-use allocation model (Section 4.2.3) to identify suitable locations to expand irrigated areas. Climate is used as input in LPJmL to determine potential evapotranspiration, and the precipitation input to the water balance (Gerten et al., 2004). The Crop and grass component (Section 6.2), which is also part of LPJmL, calculates irrigation water demand based on crop characteristics, soil moisture and climate. If the amount of water available for irrigation is limited, water stress will occur which leads to reduction of crop yields calculated by the Crop and grass module (Section 6.2).

The natural hydrological cycle

The Water module in LPJmL consists of a vertical water balance (Gerten et al., 2004) and a lateral flow component (Rost et al., 2008) which are run at 0.5 degree resolution in daily time steps (Figure 6.3.1). The soil in each grid cell is represented by a two-layer soil column of 0.5 and 1.0 m depth, partly covered with natural vegetation or crops.

The potential evapotranspiration rate in each grid cell depends primarily on net radiation and temperature, and is calculated using the Priestley-Taylor approach (Gerten et al., 2004). The actual evapotranspiration is calculated as the sum of three components: evaporation of water stored in the canopy (interception), bare soil evaporation and plant transpiration (Gerten et al., 2004). Water storage in the canopy is a function of vegetation type, leaf area index (LAI) and precipitation amount. Plant transpiration is modelled as the minimum of atmospheric demand and plant water supply. Plant water supply depends on the plant-dependent maximum transpiration rate and relative soil moisture. Soil evaporation occurs in the proportion of land in the grid cell that is not covered by vegetation. It equals potential evaporation when the soil moisture of the upper 20 cm is at field capacity, and declines linearly with relative soil moisture.

Precipitation reaching the soil (throughfall, precipitation minus interception) either accumulates as snow or infiltrates into the soil. Snowmelt is calculated using a simple degree-day method (Gerten et al., 2004). The soil is parameterised as a bucket model. The status of soil moisture of the two soil layers is updated daily, accounting for throughfall, snowmelt, evapotranspiration, percolation and runoff. Percolation rates for the two soil layers depend on soil type and decline exponentially with soil moisture. Total runoff is calculated as water in excess of field capacity from the two soil layers and water percolating through the second soil layer. The current version of LPJmL has no explicit representation of groundwater recharge, but a groundwater scheme is under development. The daily (subsurface) runoff includes the renewable fraction of groundwater, but without any time delay.

All runoff is routed daily through a gridded river network, representing a system of rivers, natural lakes and reservoirs, using a simple routing algorithm (Rost et al., 2008). Local runoff is added to surface water storage in the cell, and subsequently flows downstream at a constant flow velocity of 1 m s^{-1} until reaching a lake or reservoir. Water accumulates in lakes and reservoirs, and outflow depends on actual storage relative to the maximum storage capacity (for lakes) and the operational purpose of the reservoir (Biemans et al., 2011). For man-made reservoirs, see further below (Biemans et al., 2011)

Supply and demand for irrigation water

Water availability and demand in agriculture is simulated with LPJmL's irrigation algorithm and an algorithm to simulate the operation of large reservoirs to supply water to irrigated areas (Biemans et al., 2013).

The irrigation demand submodel (Figure 6.3.1) is described in detail by Rost et al. (2008). Crop net irrigation demand is defined as the minimum atmospheric evaporative demand and the amount of water needed to fill the soil to field capacity. The irrigation withdrawal demand – the gross demand – is subsequently calculated as the product of the crop irrigation demand and a country-specific irrigation efficiency factor that reflects the type and efficiency of prevailing irrigation systems (Rost et al., 2008). The efficiency, i.e. the losses of withdrawn water during transport between withdrawal point and irrigated field depends on the type of conveyance system (e.g., open channel or pipeline). Thus, the quantity of water demanded by crops (water consumption) is always less than the quantity withdrawn (water use).

Irrigation water is extracted from the rivers and lakes in the grid cell or a neighbouring grid cell. If these local surface water sources cannot meet total demand, water is extracted from nearby reservoirs, if available. Finally, water can be supplied from an unlimited source that can be interpreted as non-sustainable groundwater or water imported from another basin. By excluding these water sources in a series of model runs, irrigation water supply and crop production can be attributed to different water sources.

Large reservoirs

Some 50% of global river systems are regulated by dams, most of which are in basins where there is irrigation and economic activity (Nilsson et al., 2005). The main purpose of approximately one-third of all large reservoirs is irrigation. Thus, in estimating agricultural water use, man-made reservoirs have to be taken into account.

The reservoir operation module in LPJmL (Biemans et al., 2011) distinguishes three types of reservoirs: reservoirs used primarily for irrigation; reservoirs used primarily for other purposes (e.g., hydropower and flood control) but also for irrigation; and reservoirs not used for irrigation. Each type of reservoir is managed differently. The outflow of irrigation reservoirs follows the temporal pattern of irrigation demand, whereas the other reservoirs are intended to release equal quantities of water throughout the year. Water from irrigation reservoirs is supplied to downstream irrigated areas.

Water demand in other sectors

IMAGE-LPJmL only calculates agricultural water demand internally, and water demand in other sectors is calculated separately. For household and manufacturing sectors, data and algorithms are adopted from the WaterGAP model (Alcamo et al., 2003). For the electricity sector, a process-based estimation is used based on the study by Davies et al. (2013), and livestock water demand follows from the number of animals estimated in the Livestock systems model (see Section 4.2.4), with the water demand per head adjusted for climate conditions. Domestic demand is a function of population size and per capita income, corrected for the proportion of the population without access to a piped water supply (see Section 7.7). Manufacturing demand is a function of industrial value added, corrected for changes in sector composition, such as the structural change factor used for Energy demand (see Section 4.1.1).

For the electricity sector, a technology-based approach was adopted from the study by Davies et al. (2013). The type of power plant (e.g., standard steam cycle, combined steam cycle) determines the demand for cooling capacity. As plants cogenerating heat and power require less cooling capacity, demand is also corrected for these plants. In addition, the type of cooling facility determines the quantity of water required. Once-through cooling systems use large volumes of surface water that are returned almost entirely to the water body from which they were extracted, albeit at an elevated temperature. Wet cooling towers exploit the evaporation heat capacity of water and thus require much lower water volumes. However, a significant part of the cooling water evaporates during the process and does not return to the original water body. In some regions, cooling ponds are used, where cooling water is pumped and recycled in a closed loop, with water demand somewhere between the once-through and wet tower cooling systems. Finally, dry cooling systems are deployed that use air as a coolant and thus do not require cooling water. Based on data from Davies et al. (2013), market share for types of cooling systems – for each power plant type distinguished in TIMER in each world region – are combined with energy input requirements to obtain the total water demand for the electricity sector.

Water extractions

Water requirements in other sectors are extracted from local surface water, if available (rather than from reservoirs). Meeting the demand from these sectors receives priority over water withdrawal for irrigation.

The current version of IMAGE-LPJmL does not take into account the water needs of ecosystems, or other uses, such as shipping and recreation. However, a new module to calculate environmental flow requirements is under development (Pastor et al., submitted). This module, which constrains water withdrawals so that a minimum environmental flow is guaranteed, will be used to identify possible areas of conflict between water users.

Impact indicators

Water stress is often presented as a spatial and temporal average of water withdrawal-to-availability ratio at basin or country level. The population living with water stress is estimated by overlaying such a water-stress (or water availability) map with a population density map. These indicators are used to present IMAGE-LPJmL results (for instance, in the OECD Environmental Outlook, see Figure 6.3.2) but they mask the potential occurrence of water shortages in the short-term or on sub-basin scale. Thus, water stress should also be calculated at higher spatial and temporal resolutions, as can principally be done with LPJmL (see Biemans, 2012).

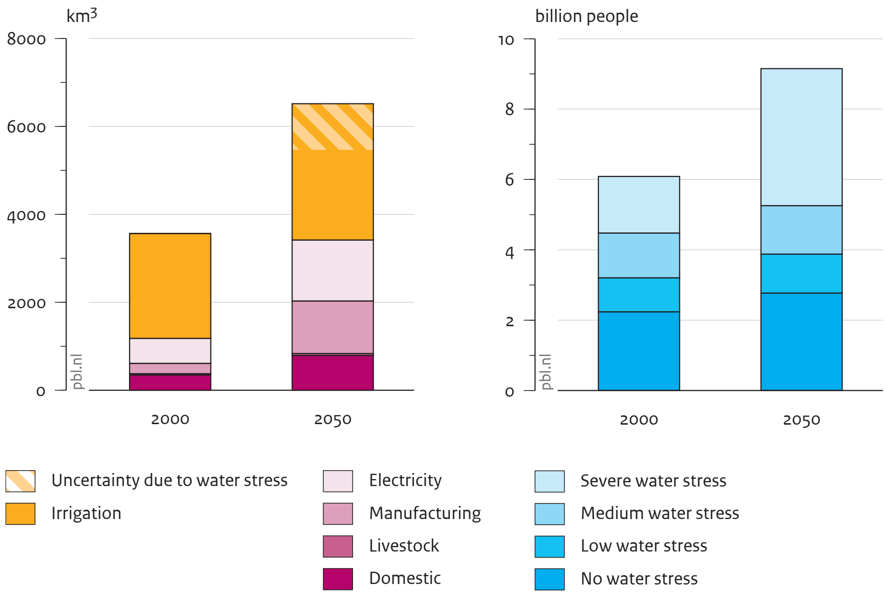
The impacts of water stress differ per sector, but the indicators described above do not provide deeper insight into these impacts. In addition to the general water stress indicators, the model also considers production reduction in irrigated agriculture due to limited water availability as an indicator of agricultural water stress (Biemans, 2012).

Figure 6.3.2

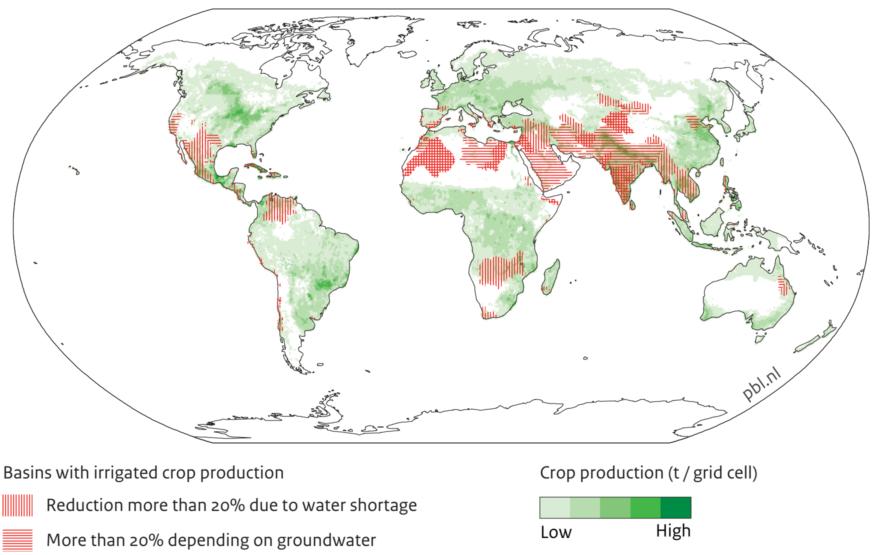
Global water demand and water stress under a baseline scenario

Global water demand

Population in water-stressed basins



Regions vulnerable to crop production losses due to irrigation water shortage



Source: OECD 2013; Biemans et al. 2012

As a result of increasing water demand and climate change, the number of people living under water stress is projected to increase (top, OECD 2012), and more regions might face a reduction in crop production due to irrigation water shortage (bottom, Biemans 2012).

3. Policy issues

Baseline developments

In baseline scenarios, water use is typically projected to increase rapidly. This can be illustrated in the baseline scenario study for the OECD Environmental Outlook to 2050 (OECD, 2012) in which water demand is projected to increase by 53% globally, mostly due to a high increase in non-agricultural water use (Figure 6.3.2). However, this baseline scenario did not consider irrigated area expansion, which is expected to further increase demand for irrigation water. As a result of the increase in total water demand, and a change in water availability due to climate change, the number of people living in medium to severely water stressed basins will increase by 80%, according to this baseline (Figure 6.3.2).

Expansion of rain-fed and irrigated croplands together with increased crop yields are projected in studies on the future of the global food system (Fischer et al., 2005; Molden, 2007; FAO, 2012a; Gerten et al., 2013). However, irrigation expansion and related increases in crop yields may not be feasible because of water scarcity.

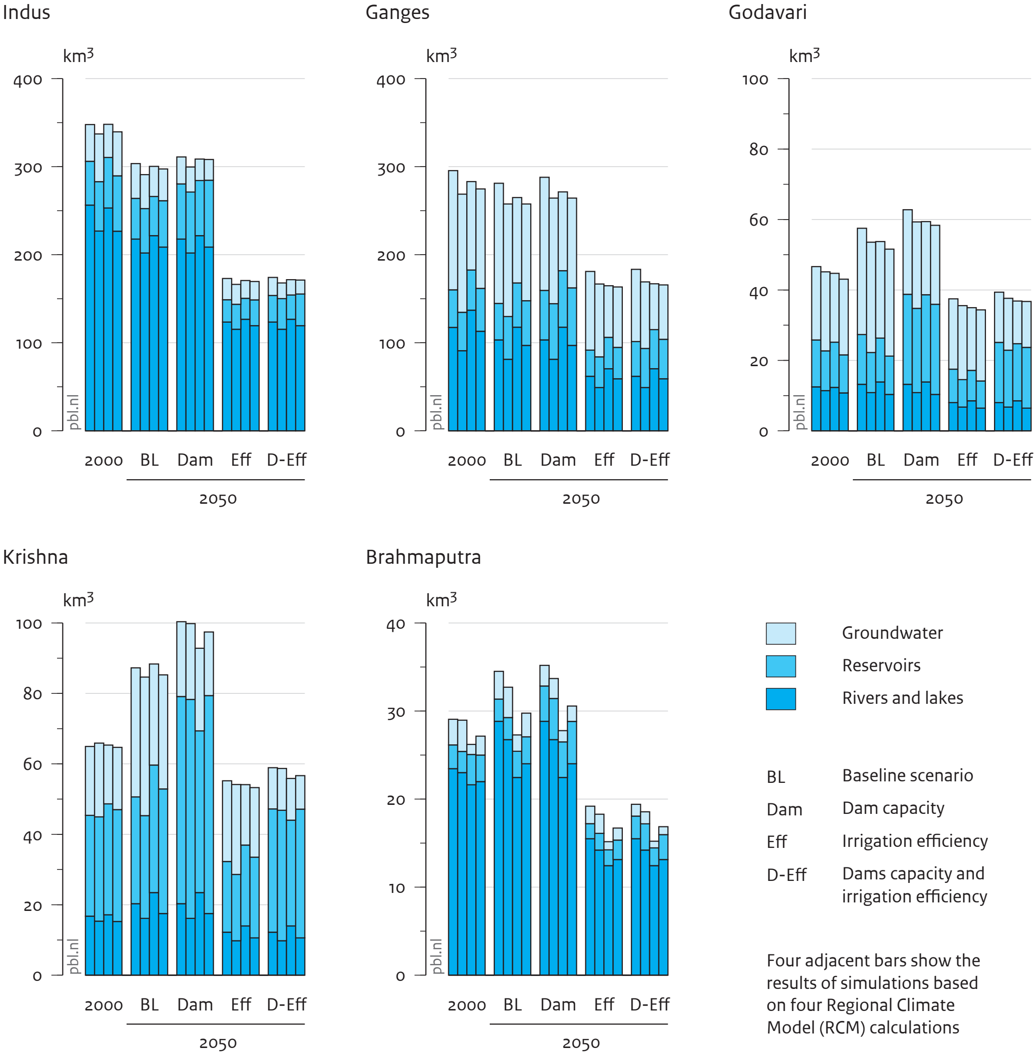
Policy interventions

Several water-related policy interventions can be assessed with IMAGE-LPJmL, including improved rainwater management, improved irrigation efficiency, increasing storage capacity and land-use related interventions. For example, Rost et al. (2009) evaluated the effect of improved rainwater management on crop production by decreasing soil evaporation and increasing rainwater harvesting. Biemans et al. (2012) tested the effect of improved irrigation efficiency and expansion of storage capacity on irrigation water demand and available sources of supply for five river basins on the Indian subcontinent (Figure 6.3.3).

In combination with the crop model, the effect of land-use related policy interventions can be addressed, such as changes in crop types or improved land and water allocation.

Figure 6.3.3

Contribution of water sources to meet irrigation water demand



Source: Biemans et al. 2012

Three of the five water basins on the Indian subcontinent strongly rely on groundwater resources to meet irrigation water demand. Doubling the capacity of large dams can increase the amount of irrigation water available in some basins. In all basins, improved irrigation efficiency leads to a significant reduction in water required for irrigation.

4. Data, uncertainties and limitations

Data

The Hydrology module of LPJmL uses external data on the river flow direction (Döll and Lehner, 2002), dams and reservoirs, and soil properties (Table 6.3.1).

Uncertainty in water availability

Three water-extraction sources are distinguished in LPJmL: rivers and natural lakes, man-made reservoirs, and groundwater. Simulations of water availability from all sources suffer from uncertainty.

Inter-comparison of global hydrology models shows that LPJmL simulations of monthly discharges are in agreement with estimates of other global hydrology models (Haddeland et al., 2011). However, a validation of simulated discharges with observations for 300 locations worldwide (Biemans et al., 2009) showed that LPJmL overestimates discharge from some basins in the tropics, but underestimates discharges from several arctic basins. The underestimations in the Arctic may be explained to a large extent by known errors in precipitation input data. The overestimations in the (sub)tropics are caused by processes not described in LPJmL, such as evaporation losses from wetlands, tropical rivers and floodplains.

Because uncertainties in precipitation input data propagate through to the calculation of river discharge, multiple climate change scenarios need to be used in assessment of future water availability, as in Gerten et al. (2013).

LPJmL's reservoir operation scheme simulates management of 7000 of the world's largest reservoirs, as well as withdrawal and distribution of irrigation water from those reservoirs. Biemans et al. (2011) calculated that reservoirs contribute annually around 500 km^3 of irrigation water. As there are no other studies that quantify the contribution of reservoirs to irrigation, the uncertainty in this estimation is difficult to determine.

Globally, groundwater contributes around one third of the water supply used for irrigation. Groundwater availability is not explicitly included in the model and there are no global data on the quantity of usable groundwater storage. Siebert (2010) provides such an assessment without differentiating between renewable and fossil groundwater. As it is unknown how long various groundwater reservoirs could continue to be exploited, uncertainty about future availability of groundwater resources results in uncertainty in the assessment of future water stress.

Uncertainty in water demand
Several studies have shown that the key factor in increased water stress is increasing water demand rather than changing climate (Vörösmarty et al., 2000; Biemans, 2012). Thus, scenario assumptions on expansion of irrigated areas and increases in water-use efficiency in all sectors influence assessment of future water stressed areas. Although there is consensus that water demand will increase as population grows, the extent of this increase largely depends on scenario assumptions on the size of irrigation areas and on efficiency improvements.

Uncertainty about future water availability, water demand and water stress propagates to other model components, for example to crop yield simulations and future cropland allocations. More extensive assessment of uncertainties with respect to the quantification of agricultural water availability and demand can be found in Biemans (2012).

5. Key publications

Biemans H. (2012). Water constraints on future food production, PhD thesis, Wageningen University and Research Centre, The Netherlands.

Biemans H, Haddeland I, Kabat P, Ludwig F, Hutjes RWA, Heinke J, Von Bloh W and Gerten D. (2011). Impact of reservoirs on river discharge and irrigation water supply during the 20th century. *Water Resources Research* 47(3), pp. W03509, DOI: 10.1029/2009wr008929.

Gerten D, Lucht W, Ostberg S, Heinke J, Kowarsch M, Kreft H, Kundzewicz ZW, Rastgooy J, Warren R and Schellnhuber HJ. (2013). Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters* 8(3), DOI: 10.1088/1748-9326/8/3/034032.

6. Input/Output Table

Table 6.3.1
Input in and output from the water model of LPJmL

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Irrigation conveyance efficiency	Ratio of water supplied to the irrigated field to the quantity withdrawn from the water source, determining the quantity of water lost during transport. This parameter is defined at country level.	3
Irrigation project efficiency	Ratio of quantity of irrigation water required by the crop (based on soil moisture deficits) to the quantity withdrawn from rivers, lakes, reservoirs or other sources. This parameter is given at country level.	3
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Crop irrigation water demand - grid	Water requirements for crop irrigation, calculated as daily moisture deficit during the growing season.	6.2
External datasets		
Digital water network - grid	Digital water network DDM30 describing drainage directions of surface water, with each cell only draining into one neighbouring cell, organising cells to river basins.	Döll and Lehner (2002)
LOD (location of dams and reservoirs)	Location, building year, purpose and size of 7000 largest reservoirs.	Lehner et al. (2011)
Soil properties - grid	Soil types and soil properties, such as soil texture, soil depth and water holding capacity.	HWSD database (FAO et al., 2009)
Output	**Description**	**Use (section)**
River discharge - grid	Average flow of water through each grid cell.	4.2.3, 7.3, 7.6
Irrigation water supply - grid	Water supplied to irrigated fields; equal to irrigation water withdrawal minus water lost during transport, depending on the conveyance efficiency.	6.1, 6.2
Water withdrawal other sectors - grid	Total annual water withdrawal by non-agricultural sectors.	5.1
Irrigation water withdrawal - grid	Water withdrawn for irrigation, not necessarily equal to irrigation water demand, because of limited water availability in rivers, lakes, reservoirs and other sources.	5.1
Water stress - grid	Water stress expressed as the ratio of mean annual water demand to availability, aggregated to basin level (0.2-0.4 medium water stress; >0.4 severe water stress).	Final output

6.4 Nutrients

Lex Bouwman, Arthur Beusen, Peter van Puijenbroek

Key policy issues

- How will the increasing use of fertilisers affect terrestrial and marine ecosystems, with possible consequences for human health?
- To what extent can the negative impacts be reduced by more efficient nutrient management and wastewater treatment, while retaining the positive effects on food production and land productivity?

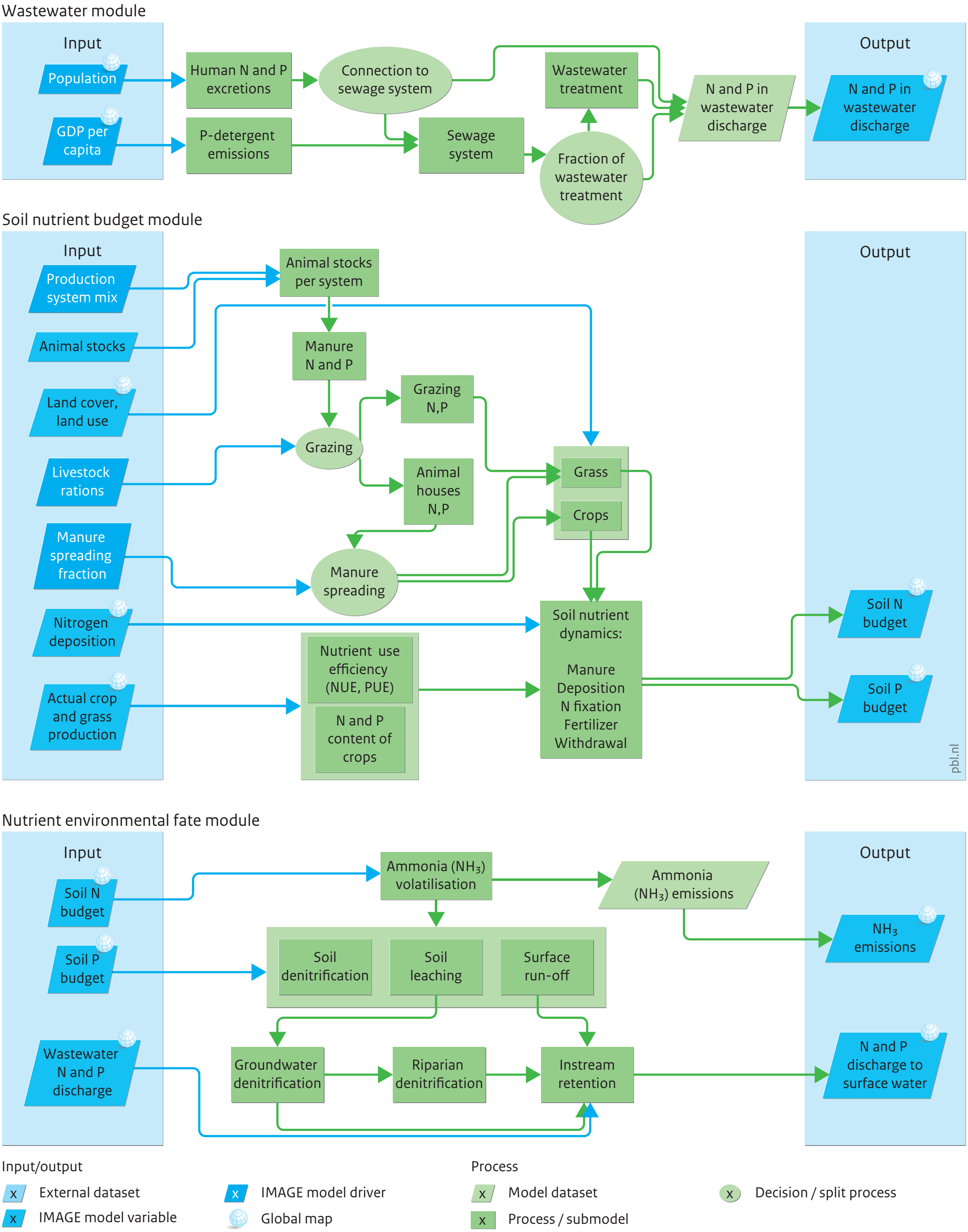
1. Introduction

Human activity has accelerated the Earth's biogeochemical nitrogen (N) and phosphorus (P) cycles through increasing fertiliser use in agriculture (Bouwman et al., 2013c). Increased use of N and P fertilisers has raised food production to support the rapidly growing world population, and increasing per capita consumption particularly of meat and milk (Galloway et al., 2004).

The side effect is that significant proportions of the mobilised N are lost through ambient emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitric oxide (NO). Ammonia contributes to eutrophication and acidification when deposited on land. Nitric oxide plays a role in tropospheric ozone chemistry, and nitrous oxide is a potent greenhouse gas. Moreover, large proportions of mobilised N and P in watersheds enter the groundwater through leaching, and are released to surface waters through groundwater transport and surface runoff. Subsequently, nutrients in streams and rivers are transported to coastal marine systems, reduced by retention but augmented by releases from point sources, such as sewerage systems and industrial facilities.

This has resulted in negative impacts on human health and the environment, such as groundwater pollution, loss of habitat and biodiversity, an increases in the frequency and severity of harmful algal blooms, eutrophication, hypoxia and fish kills (Diaz and Rosenberg, 2008; Zhang et al., 2010). The harmful effects of eutrophication have spread rapidly around the world, with large-scale implications for biodiversity, water quality, fisheries and recreation, in both industrialised and developing regions (UNEP, 2002). Input of nutrients in freshwater and coastal marine ecosystems also disturbs the stoichiometric balance of N, P and Si (silicon) (Rabalais, 2002) affecting total plant production and the species composition in ecosystems.

Figure 6.4.1
Nutrient model of IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 6.4.1).

To assess eutrophication as a consequence of increasing population, and economic and technological development, IMAGE 3.0 includes a nutrient model, which comprises three modules:

- Wastewater module calculating nutrient flows in wastewater discharges (Figure 6.4.1, top);
- Soil nutrient budget module describing all input and output of N and P in soil compartments (Figure 6.4.1, middle);
- Nutrient environmental fate describing the fate of soil nutrient surpluses and wastewater nutrients in the aquatic environment (Figure 6.4.1, bottom).

2. Model description

Wastewater

Urban wastewater contains N and P emitted by households and industries that are connected to a sewerage system, and households with sanitation but without a sewerage connection.

N discharges to surface water ($E_{\mathrm{sw}}^{\mathrm{N}}$ in kg per person per year) are calculated as follows (Van Drecht et al., 2009; Morée et al., 2013):

$$E_{\mathrm{sw}}^{\mathrm{N}} = E_{\mathrm{hum}}^{\mathrm{N}} \, D(1 - R^{\mathrm{N}}) \qquad (6.4.1)$$

where $E_{\mathrm{hum}}^{\mathrm{N}}$ is human N emissions (kg per person per year), *D* is the proportion of the total population connected to public sewerage systems (no dimension), R^{N} is the overall removal of N through wastewater treatment (no dimension).

Total P emissions to surface water are calculated in a similar way, but also include estimates of P emissions to surface water resulting from the use of P-based dishwasher and laundry detergents. Nutrient removal by wastewater treatment *R* is based on the relative contribution of four classes of treatment (none, primary, secondary and tertiary treatment). *D* is calculated from the proportion of households with improved sanitation. *D* and R by treatment class are scenario variables.

Soil nutrient budget

The soil budget approach (Bouwman et al., 2009; Bouwman et al., 2013c) considers all N and P inputs and outputs for IMAGE grid cells. N input terms in the budgets include application of synthetic N fertiliser (N_{fert}) and animal manure (N_{man}), biological N fixation (N_{fix}), and atmospheric N deposition (N_{dep}). Output terms include N withdrawal from the field through crop harvesting, hay and grass cutting, and grass consumed by grazing animals (N_{withdr}).

The soil N budget (N_{budget}) is calculated as follows:

$$N_{budget} = N_{fert} + N_{man} + N_{fix} + N_{dep} - N_{withdr} \tag{6.4.2}$$

The same approach is used for P, with input terms being animal manure and fertiliser. The soil nutrient budget does not include nutrient accumulation in soil organic matter for a positive budget (surplus), or nutrient depletion due to soil organic matter decomposition and mineralisation. With no accumulation, a surplus represents a potential loss to the environment. For N this includes NH_3 volatilisation (see Section 5.2), denitrification, surface runoff and leaching. For P, this is surface runoff.

For spatial allocation of the nutrient input to IMAGE grid cells, grass and the crop groups in IMAGE (temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops, other crops, energy crops) and grass are aggregated to five broad groups. These groups are grass, wetland rice, leguminous crops, other upland crops and energy crops for both mixed and pastoral production systems (see Section 4.2.4).

Fertiliser: Fertiliser use is based on nutrient use efficiency, representing crop production in kilograms of dry matter per kilogram of fertiliser N (NUE) and P (PUE). NUE and PUE vary between countries because of differences in crop mix, attainable yield potential, soil quality, amount and form of N and P application and management. In constructing scenarios on fertiliser use, data on the 1970–2005 period serve as a guide to distinguish countries with an input exceeding crop uptake (positive budget or surplus) from countries with a deficit. Generally, farmers in countries with a surplus are assumed to be increasingly efficient in fertiliser use (increasing NUE and PUE). In countries with nutrient deficits, an increase in crop yields is only possible with an increase in the nutrient input. Initially, this will lead to decreasing NUE and PUE, showing a decrease in soil nutrient depletion due to increased fertiliser use.

Manure: Total manure production is computed from animal stocks and N and P excretion rates (Figure 6.4.1, middle). IMAGE uses constant N and P excretion rates per head for dairy and non-dairy cattle, buffaloes, sheep and goats, pigs, poultry, horses, asses, mules and camels. Constant excretion rates imply that the N and P excretion per unit of product decreases with increased milk and meat production per animal.

N and P in the manure for each animal category are spatially allocated to mixed and pastoral systems. In each country and system, the manure is distributed over three management systems: grazing; storage in animal housing and storage systems; and manure used outside the agricultural system for fuel or other purposes. The quantity of manure assigned to grazing is based on the proportion of grass in feed rations (Figure 6.4.1, middle).

Stored animal manure available for cropland and grassland application includes all stored and collected manure, excluding ammonia volatilisation from animal houses and storage systems. In general, IMAGE assumes that 50% of available animal manure from storage systems is applied to arable land and the rest to grassland in industrialised countries. In most developing countries, 95% of the available manure is spread on croplands and 5% on grassland, thus accounting for the lower economic importance of grass compared to crops in these countries. In the European Union, maximum manure application rates are 170 to 250 kg N per ha, reflecting current regulations.

Biological N_2 fixation: Data on biological N_2 fixation by leguminous crops (pulses and soybeans) are obtained from the N in the harvested product (see nutrient withdrawal) following the approach of Salvagiotti et al. (2008). Thus any change in the rate of biological N_2 fixation by legumes is the result of yield changes for pulses and soybeans. In addition to leguminous crops, IMAGE uses an annual rate of biological N_2 fixation of 5 kg N per ha for non-leguminous crops and grass, and 25 kg N per ha for wetland rice. N fixation rates in natural ecosystems were based on the low estimates for areal coverage by legumes (Cleveland et al., 1999) as described by Bouwman et al. (2013a).

Atmospheric deposition: Deposition rates for historical and future years are calculated by scaling a N deposition map for 2000 (obtained from atmospheric chemistry transport models), using emission inventories for the historical period and N gas emissions in the scenario considered. IMAGE does not include atmospheric P deposition.

Nutrient withdrawal: Withdrawal of N and P in harvested products is calculated from regional crop production in IMAGE and the N and P content for each crop, which is aggregated to the broad crop categories (wetland rice, leguminous crops, upland crops and energy crops). IMAGE also accounts for uptake by fodder crops. N withdrawal through grass consumption and harvest is assumed to amount to 60% of all N input (manure, fertiliser, deposition, N fixation), excluding NH_3 volatilisation. P withdrawal through grazing or grass cutting is calculated as a proportion of 87.5% of fertiliser and manure P input. The rest is assumed to be lost through surface runoff. In calculating spatially explicit nutrient withdrawal, a procedure is used to downscale regional crop production data from IMAGE to country estimates for nutrient withdrawal based on distributions in 2005.

Nutrient environmental fate

Nutrient losses from the plant-soil system to the soil-hydrology system are calculated from the soil nutrient budgets (Bouwman et al., 2013a). For N, the budget is corrected for ammonia volatilisation from grazing animals and from fertiliser and manure spreading (see Section 5.2, Emissions). P not taken up by plants is generally bound to soil particles, with the only loss pathway being surface runoff. N is more mobile and is transported via surface runoff and through soil, groundwater and riparian zones to surface water.

Soil denitrification and leaching: Denitrification is calculated as a proportion of the soil N budget surplus based on the effect of temperature and residence time of water and nitrate in the root zone, and the effects of soil texture, soil drainage and soil organic carbon content. In a soil budget deficit, IMAGE assumes that denitrification does not occur. Leaching is the complement of the soil N budget.

Groundwater transport, surface runoff and denitrification: Two groundwater subsystems are distinguished. One is the shallow groundwater system representing interflow and surface runoff for the upper 5 m of the saturated zone, with short travel times for the water to enter local surface water at short distances or to infiltrate the deep groundwater system. The other is the deep system with a thickness of 50 m with generally long travel times draining to larger streams and rivers. Deep groundwater is assumed to be absent in areas of non-permeable, consolidated rocks or in the presence of surface water. Denitrification during groundwater transport is based on the travel time and the half-life of nitrate. The half-life depends on the lithological class (1 year for schists and shales containing pyrite, 2 years for alluvial material, and 5 years for all other lithological classes). Flows of water and nitrate from shallow groundwater to riparian zones are assumed to be absent in areas with surface water bodies, where the flow is assumed to bypass riparian zones flowing directly to streams or rivers.

Denitrification in riparian areas: The calculation of denitrification in riparian areas is similar to that in soils, but with two differences: a biologically active layer of 0.3 m thickness is assumed instead of 1 m for other soils; and the approach includes the effect of pH on denitrification.

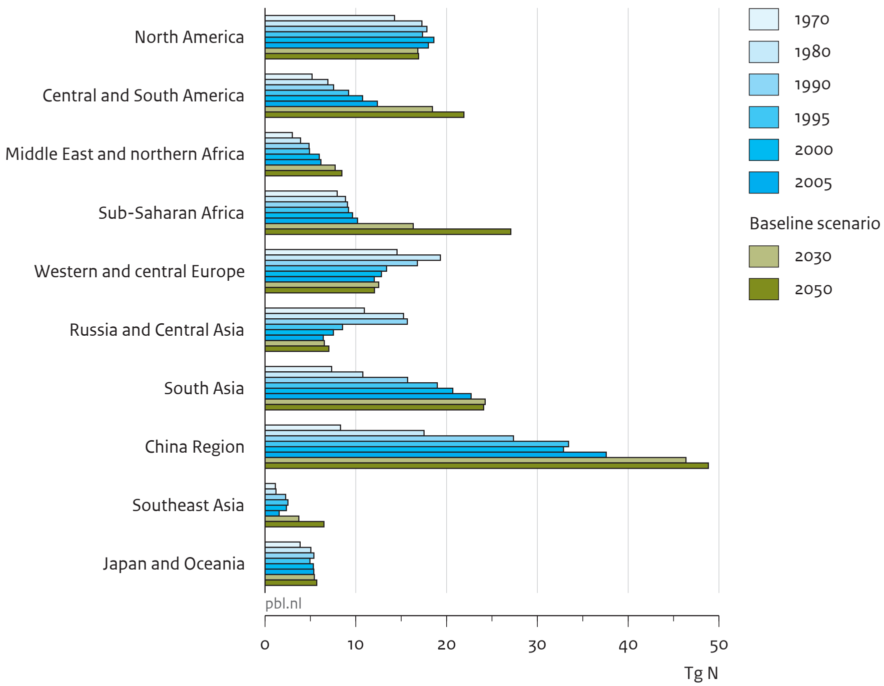
In-stream nutrient retention: The water that enters streams and rivers through surface runoff and discharges from groundwater and riparian zones is routed through stream and river channels, and passes through lakes, wetlands and reservoirs. The nutrient retention in each of these systems is calculated on the basis of the nutrient spiralling ecological concept, which is based on residence time and temperature as described in (Beusen et al., submitted).

3. Policy issues

Baseline developments

Under baseline scenarios of IMAGE, N surpluses generally increase. For example, in the Rio+20 baseline scenario, the N surplus increases by 35% globally in the period 2002-2050 (Figure 6.4.2). This is the result of decreasing trends in North America, Western Europe and Japan as a result of increasing nutrient use efficiency, and stabilisation in India. In all other regions, N surpluses increase, particularly in Sub-Saharan Africa and Southeastern Asia as a result of increasing fertiliser use to halt soil nutrient depletion (Figure 6.4.2). The situation is similar for P, with large increases in developing countries.

Figure 6.4.2
Soil nitrogen budget per region



Source: PBL 2012

The nitrogen soil budgets in Northern America, Europe, Russia and Central Asia, Japan and Oceania are stable or decreasing after 2005, they are projected to strongly increase in many other regions in a baseline scenario.

Policy interventions

Economic developments and policy interventions may modify individual terms in the soil nutrient budget (Equation 6.4.2), and the fate of nutrients in the environment. For example, agricultural demand (Section 4.2.1) affects:

- Production of leguminous crops (pulses and soybeans) and biological N fixation as a consequence;
- Meat and milk production and thus animal manure production;
- Crop production and fertiliser use.

The IMAGE soil nutrient model includes options to reduce nutrient surpluses in agriculture or nutrients in wastewater, and strategies to improve resource use efficiency. Wastewater strategies that can be assessed with tools available in the nutrient model of IMAGE include:

- Increasing access to improved sanitation and connection to sewerage systems;
- Construction of wastewater treatment plants;
- Substituting synthetic fertilisers with fertilisers produced from human excreta. This option has no consequences for nutrient budgets, but reduces wastewater flows.

IMAGE also addresses strategies for reducing nutrient surpluses in agriculture, including the five options illustrated in Figure 6.4.3:

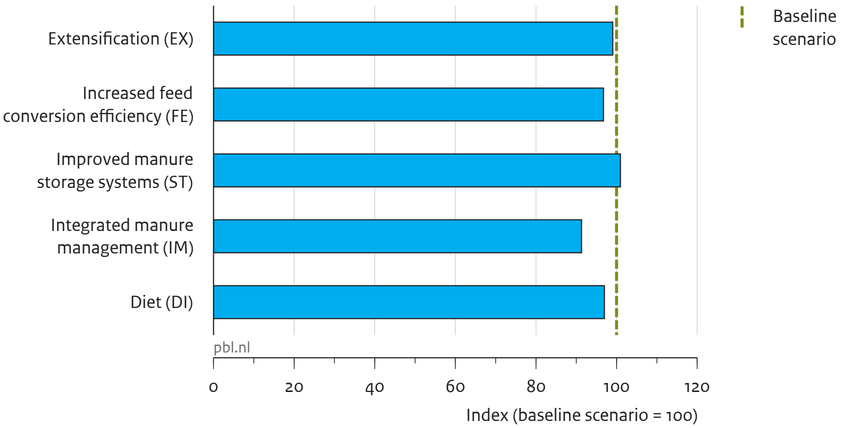
- Extensification (EX), assuming for example that 10% of ruminant production in mixed and industrial systems shifts to pastoral production systems.
- Increased feed conversion efficiency (FE), assuming for example 10% reduction in N and P excretion for cattle, pigs, poultry and small ruminants in mixed and industrial systems. This is achieved by increasing the use of concentrates.
- Improved manure storage systems (ST), considering for example 20% lower NH_3 emissions from animal housing and storage systems. This means that the animal manure used for spreading contains 5% more N than under the baseline scenario.
- Integrated manure management (IM) where, for example, all manure under the baseline scenario ends up outside the agricultural system (e.g., manure used as fuel, see Figure 6.4.1) and is recycled in crop systems to substitute fertiliser. In addition, integration of animal manure in crop systems is improved, particularly in industrialised countries.
- Dietary changes (DI), for example, assume that by 2050, 10% of beef consumption under the baseline scenarios is replaced by poultry meat in all producing regions, without accounting for changes in agricultural trade.

Extensification, increased feed efficiency and reduced ammonia emissions from stables (cases EX, FE and ST) have minor effects on the global soil N budget (Figure 6.4.3). However, better integration of animal manure in crop production systems (IM), primarily in industrialised countries, and a change in the human diet with poultry replacing ruminant meat (DI) would have major effects on the global soil N budget.

Other options that can be assessed using scenario variables from other parts of IMAGE include:

- Consequences of changes in crop production systems, such as increasing crop yields, that would improve fertiliser use efficiency;
- Consequences of changes in livestock production systems such as better management leading to lower excretion rates;
- Changes in the distribution of total production between mixed and pastoral systems;
- Changing human diets leading to changing production volumes.

Figure 6.4.3
Global soil nitrogen budget under a number of policy interventions, 2050



Source: Bouwman et al. 2013

Several policy interventions can lead to a reduction in the global soil nitrogen budget compared to a baseline scenario (Bouwman et al., 2013c).

4. Data, uncertainties and limitations

Data

The data stem from various parts of IMAGE, such as land cover, biomes, crop production and allocation, livestock, fertiliser use and nutrient excretion rates. Environmental data include temperature and precipitation, runoff, and soil properties.

External data are used in determining historical N excretion rates, manure spreading and fertiliser use efficiency, but their development in the future is a scenario assumption. Additional information used only in this section includes lithology, relief and slope of the terrain. Additional data used in the nutrient budget model include subnational data as used for the United States, India, Brazil and China.

Uncertainties

With regard to uncertainties, the budget calculations and individual input terms for 2000 have been found to be in close agreement (Bouwman et al., 2009) with detailed country estimates for the member countries of the Organisation for Economic Co-operation and Development (OECD, 2012).

However, uncertainty is larger for some budget terms than for others. Data on fertiliser use are more reliable than on N and P animal excretions, which are calculated from livestock data (FAO, 2012a) and excretion rates per animal category. Data on crop nutrient withdrawal are less certain than on crop production, because the withdrawal is calculated with fixed global nutrient contents of the harvested proportions of marketed crops. In addition to uncertainty in nutrient contents, major uncertainties arise from insufficient data, for instance, on crops that are not marketed and on the use of crop residues. This leads to major uncertainties about nutrient withdrawal.

Sensitivity analysis (Beusen et al., 2008) has shown that the main determinants of the uncertainty in the nutrient model are N excretion rates; NH_3 emission rates from manure in animal housing and storage systems; the proportion of time that ruminants graze, the proportion of non-agricultural use of manure in mixed and industrial systems; and animal stocks.

5. Key publications

Morée AL, Beusen AHW, Bouwman AF and Willems WJ. (2013). Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. *Global Biogeochemical Cycles* 27, pp. 1–11, DOI: 10.1002/gbc.20072.

Bouwman AF, Beusen AHW and Billen G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Global Biogeochemical Cycles* 23, DOI: 10.1029/2009GB003576.

Bouwman AF, Beusen AHW, Griffioen J, Van Groenigen JW, Hefting MM, Oenema O, Van Puijenbroek PJTM, Seitzinger S, Slomp CP and Stehfest E. (2013a). Global trends and uncertainties in terrestrial denitrification and N_2O emissions. *Philosophical Transactions of the Royal Society B: Biological Sciences* 368(1621), DOI: 10.1098/rstb.2013.0112.

6. Input/Output Table

Table 6.4.1
Input in and output from the nutrient model in IMAGE

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Population - grid	Number of people per gridcell (using downscaling).	3
GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	3
Production system mix	Livestock production is distributed over two systems (intensive: mixed and industrial; extensive: pastoral grazing), with specific intensities, rations and feed conversion ratios.	3
Livestock rations	Determines the feed requirements per feed type (food crops; crop residues; grass and fodder; animal products; scavenging), specified per animal type and production system (extensive/intensive).	3
Manure spreading fraction	Fraction of manure produced in staples that is spread on agricultural areas.	3
Fertiliser use efficiency	Ratio of fertiliser uptake by a crop to fertiliser applied.	3
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Actual crop and grass production - grid	Actual crop and grass production on agricultural land, based on potential yield and management intensity	6.2
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	4.2.4
Nitrogen deposition - grid	Deposition of nitrogen.	5.2
Output	**Description**	**Use (section)**
N and P discharge to surface water - grid	N and P discharge to surface water.	7.3
Soil N budget - grid	N budget in the soil, used to calculate fate of nitrogen in the soil-hydrology system and for determining emissions to the atmosphere.	Final output
Soil P budget - grid	P budget in the soil, used to calculate fate of nitrogen in the soil-hydrology system (residual soil P or surface runoff).	Final output
NH_3 emissions - grid	Ammonia emissions from applied nitrogen fertiliser and manure.	Final output
N and P in wastewater discharge - grid	Discharge of N and P to surface water from wastewater.	Final output

6.5 Atmospheric composition and climate

Elke Stehfest, Maarten van den Berg, Bart Strengers

Key policy issues

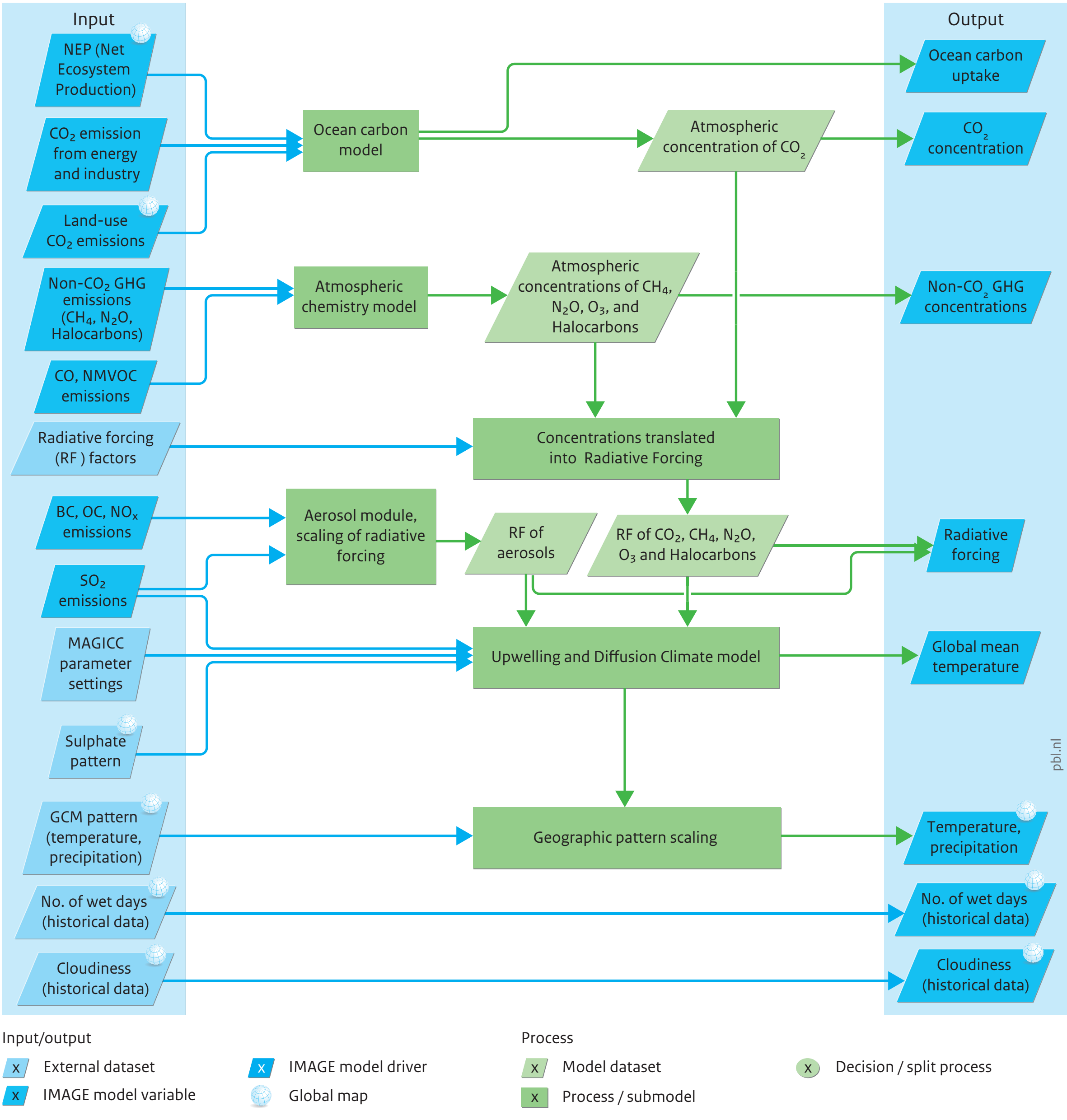
- What would be the impact of global climate change in this century without additional mitigation policies and measures?
- To what extent would the various scenarios to significantly reduce net greenhouse gas emissions lead to a reduction in climate change?
- To what extent does the uncertainty of geographical patterns in temperature and precipitation change influence future climate impacts and response strategies?

1. Introduction

Climate change is considered to be one of the most important effects of human activities on the environment. Emissions from fossil fuels, industry, land use and land-use change have increased greenhouse gas concentrations and led to almost 1 °C rise in global mean temperature on pre-industrial levels (IPCC, 2007a; IPCC, 2013). The impacts are already visible and are expected to increase in this century. Without further action, mean global temperature could increase by 2.6 – 4.8 °C (5-95 percentile, RCP8.5) by the end of this century (IPCC, 2013). Climate change impacts manifest themselves in all world regions, and affect almost all aspects of human activity.

Modelling climate change (changes in temperature and precipitation) is central in global integrated assessments of baseline developments and of climate policy options. IMAGE uses the simple climate model MAGICC 6.0 (Meinshausen et al., 2011a; Meinshausen et al., 2011c) to simulate the effects of changing greenhouse gas emissions on atmospheric composition, radiative forcing and global mean temperature. MAGICC was used extensively in the Third, Fourth, and Fifth assessment reports of IPCC (Intergovernmental Panel on Climate Change) in assessing a range of greenhouse gas concentration scenarios. Since publication of these reports, MAGICC has been updated in line with results from Atmosphere-Ocean General Circulation Models (AOGCMs).

Figure 6.5.1
Atmospheric composition and climate model (based on MAGICC 6.0) in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 6.5.1).

There is still considerable uncertainty in climate change simulations, as illustrated by differences in results from various AOGCMs, in terms of mean global temperature, and even more so in geographical patterns of surface temperature and precipitation. By adjusting the values of a few of the model parameters, MAGICC 6.0 can reproduce time-dependent responses of AOGCMs (Meinshausen et al., 2011a; Meinshausen et al., 2011c). This allows IMAGE to reflect the uncertainty in AOGCM results, and to provide plausible projections of future climate-change feedbacks and impacts.

The analysis of climate impacts and feedbacks requires location-specific temperature and precipitation changes. Thus, a pattern scaling technique is applied in IMAGE by combining MAGICC results with maps on climate change from the same AOGCMs assessed in AR4 (IPCC, 2007a) and used for calibrating MAGICC. The consistent combination of AOGCM-specific parameter settings for MAGICC and matching geographical patterns of climate change make the dynamic results from IMAGE physically more consistent, and extend the range of uncertainties that can be covered to include future climate change.

2. Model description

Atmospheric gas concentrations

The IMAGE climate model (based on MAGICC 6.0, Meinshausen et al., 2011a) calculates atmospheric CO_2 concentration based on CO_2 emission data for energy, industry and land-use change (Section 5.2); terrestrial carbon balance (Section 6.1); and carbon uptake by the oceans (calculated in MAGICC on the basis of the Bern Ocean Carbon model).

Concentrations of other long-lived greenhouse gases (CH_4, N_2O, and halocarbons), and tropospheric ozone (O_3) precursors (CO, NMVOC) are calculated by MAGICC in a simple atmospheric chemistry module (Figure 6.5.1). Halocarbons and N_2O concentrations mostly show a simple mass-concentration conversion and half-life behaviour. CH_4 and ozone dynamics are more complex, with CH_4 lifetime depending on the OH concentration level, and O_3 and OH concentration levels depending on CH_4 concentrations, and NO_x, CO and NMVOC emissions (Meinshausen et al., 2011c).

Atmospheric energy balance

Change in atmospheric gas concentrations also changes the amount of radiation absorbed or transmitted by the atmosphere, and thus changes the earth's energy balance and temperature. The energy balance change is expressed as radiative forcing per gas, measured in W/m^2. In MAGICC, concentrations of long-lived greenhouse gases are translated into radiative forcing values using radiative efficiency estimates from the IPCC (Myhre et al., 2013), and radiative forcing of tropospheric ozone is calculated based on ozone sensitivity factors from MAGICC 6.0 (Meinshausen et al., 2011a; Meinshausen et al., 2011c).

However, other processes also lead to changes in the atmospheric energy balance, which are also modelled and assigned a radiative forcing value. Aerosols, such as SO_2, NO_x, and organic carbon, have a direct cooling effect by reflecting more radiation back into space (direct aerosol effect). They also interact with clouds and precipitation in many ways (indirect aerosol effect); this cloud feedback is the largest source of uncertainty in estimating climate sensitivity (Denman et al., 2007). Although also an aerosol, black carbon has a strong direct warming effect (WMO/UNEP, 2013).

Direct and indirect aerosol effects are approximated in MAGICC by scaling the radiative forcing in a reference year (mostly 2005) with the relative increase in future emissions with respect to emissions in the reference year. As MAGICC assumes radiative forcing by albedo and mineral dust to stay constant over the scenario period (Meinshausen et al., 2011a), this is also assumed in IMAGE.

Global mean temperature change

The core of MAGICC 6.0, the upwelling–diffusion climate model, calculates change in global mean temperature as a result of these radiative forcings (Meinshausen et al., 2011a; Meinshausen et al., 2011c). It is a 'four-box' model, representing the earth by a northern and southern land component, and a northern and southern ocean component.

The energy fluxes simulated by MAGICC include heat transport from the atmosphere through the mixing top layer of the ocean to lower water layers (60 layers), and heat transfer between land and ocean. Because of the slow heat transport to the ocean, the earth's temperature takes a long time to reach a new equilibrium after a change in radiative forcing. The model parameters that control heat transport and final change in global mean temperature have been calibrated to reproduce the results of 19 Global Circulation Models of AR4 (Meinshausen et al., 2011c). In addition, a medium parameterisation is available, which results in behaviour that represents the mean of these 19 model emulations.

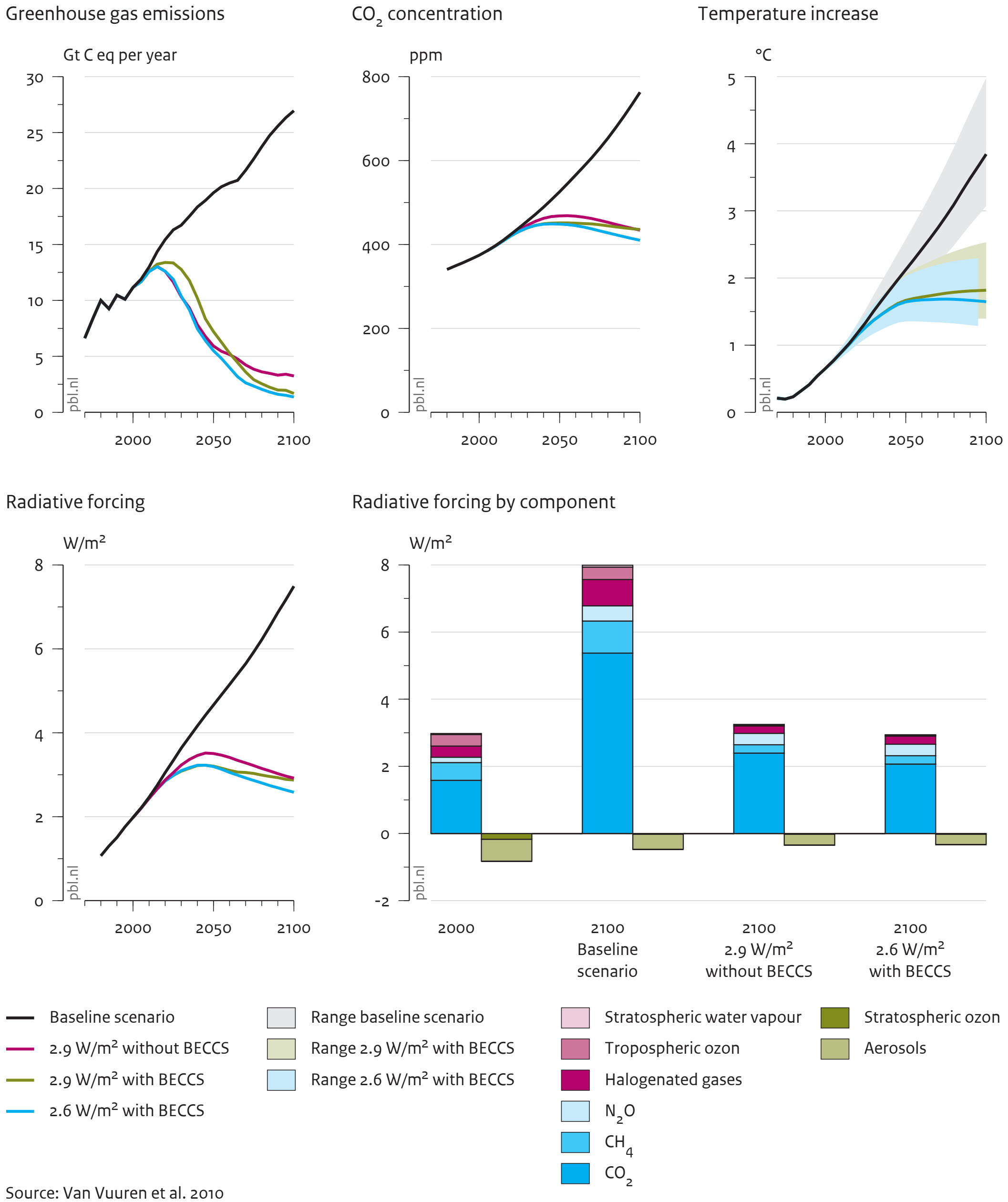
Downscaling

The global mean temperature change from MAGICC, and maps of temperature and precipitation change are used in a pattern scaling, to derive spatially explicit temperature and precipitation changes used in other IMAGE components (carbon cycle, crop model, hydrology, nutrients).

Grid-specific temperature and precipitation changes at the end of the century (2071–2100 compared to 1961–1990) from AR4 AOGCM model results (IPCC-DDC, 2007) are linearly interpolated based on the MAGGICs global mean temperature change at a certain time step, and the global mean temperature change corresponding to this map. For future calculations, the results of AR5 should be used to update the MAGICC parameterisation for all available AOGCMs, and to update the gridded patterns of climate change.

Figure 6.5.2

Greenhouse gas emissions, CO_2 concentration, temperature increase and radiative forcing under baseline and climate policy scenarios



Source: Van Vuuren et al. 2010

In the policy scenarios, emissions decrease strongly after 2020, while concentration levels only decrease or stabilise after 2050. Global mean temperature, due to inertia in the climate system, will not stabilise until the end of this century under the most ambitious climate policy scenario (2.6 W/m²).

3. Policy issues

Baseline developments

In baseline scenarios, emissions and greenhouse gas concentrations increase substantially. The increase in emissions depends on socio-economic factors, such as population growth, economic growth, technology development and lifestyle. Most medium baseline scenarios in IMAGE result in a rise in global mean temperature of about 3 to 5 °C above pre-industrial levels by 2100 (Figure 6.5.2).

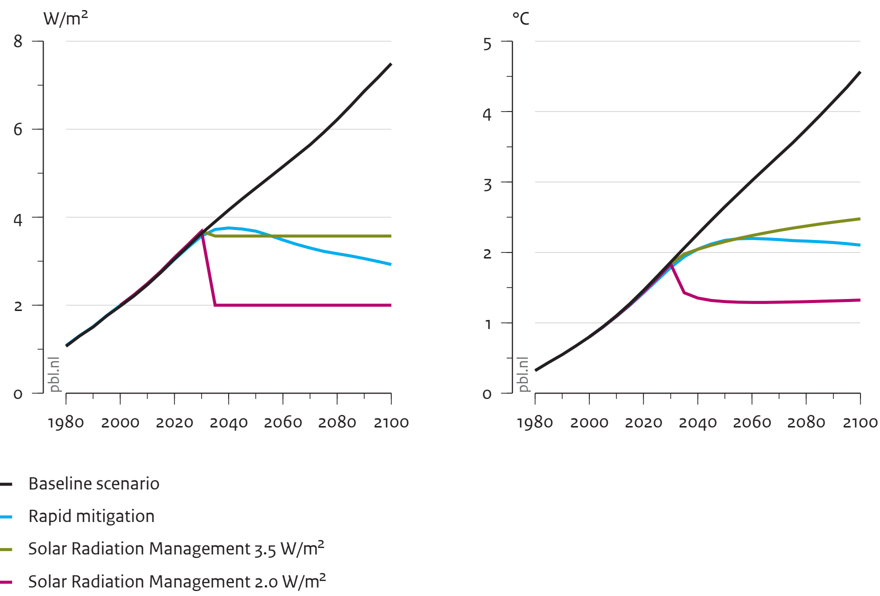
Policy interventions

Policy interventions that affect future climate range from policies on energy and agricultural systems, air pollution measures, and land-use policies to direct management of radiative forcing. For instance, the IMAGE system can be used to analyse energy efficiency, use of low-carbon fuels, reduction in non-CO_2 greenhouse gas emissions and reduction of deforestation (Overmars et al., accepted). Interventions related to policies on climate, air pollution and land use are described in Sections 8.1, 8.2 and 8.3, respectively. These measures lead to a change in emissions, and then to the expected reduction in radiative forcing and climate change.

The slow temporal dynamics of the climate system play an important role in climate policy assessments. IMAGE calculations show considerable time lag between policy introduction and impacts on climate change. Even if emissions were substantially reduced from 2020 and onwards, several decades would elapse before stabilization in temperature in the global climate system is observed (Figure 6.5.2). In addition to these standard climate measures, a range of policy interventions may play a role in the temporal dynamics of the climate system, and may be analysed using the IMAGE system:

– Mitigation in short-lived versus long-lived greenhouse gas emissions, and co-benefits with air pollution measures (Shindell et al., 2012). Short-term benefits in air quality and climate mitigation may be achieved by reducing black carbon emissions and ozone precursors.
– Non-mitigation management of global radiative forcing, such as by means of geo-engineering as shown in Figure 6.5.3 (Van Vuuren and Stehfest, 2013).

Figure 6.5.3
Radiative forcing and temperature change under baseline and policy scenarios



Source: Van Vuuren and Stehfest 2013

In addition to 'conventional' climate policy, there may be situations where urgent action on climate change is required, either via rapid mitigation, or via Solar Radiation Management (SRM) (e.g. sulphur emissions to the stratosphere). Radiative forcing is immediately stabilised at the intended level by SRM, and also temperatures are adjusted immediately (though not yet at the equilibrium level), and even faster under extreme SRM than would be possible through strong mitigation. However, substantial uncertainties and risks are related to such drastic manipulations of the radiation balance.

4. Data, uncertainties and limitations

Data

The external data used in the climate model are the radiative forcing factors from IPCC AR4 and AR5, MAGICC 6.0 parameterisations (Meinshausen et al., 2011a; Meinshausen et al., 2011c), and the patterns of climate change obtained from AOGCMs (IPCC-DDC, 2007).

Uncertainties

In general terms, the main uncertainties in the climate system relate to:
- Greenhouse gas concentration in an emission scenario
- Radiative forcing per greenhouse gas concentration
- Global mean temperature change as a result of a change in radiative forcing
- Spatial distribution of temperature and precipitation changes.

For CO_2, there is a substantial uncertainty about how much carbon enters the ocean and the terrestrial biosphere, now and in the future, and how much remains in the atmosphere. The atmospheric concentrations of other greenhouse gases after the emission release is less uncertain and also less relevant because these gases contribute less to global climate change.

In terms of radiative forcing, there is little uncertainty about the long-lived greenhouse gases (CO_2, CH_4, N_2O, and halocarbons), but AR4 identified the largest uncertainties and lowest understanding for direct and indirect aerosol effects, albedo, and tropospheric ozone (Forster et al., 2007).

IMAGE uses the mean radiative forcing factors from AR4 as best estimates for all forcing agents (Forster et al., 2007). The uncertainty in change in global mean temperature, as derived from results of AOGCM calculations, is still quite large, with climate sensitivity likely to be in the range of 2 to 4.5 °C (with lower values very unlikely, and values above 4.5 not possible to exclude). Instead of using the best estimate of 3 °C (Randall et al., 2007), this uncertainty can be accounted for by emulating different AOGCMs with the MAGICC model.

For the spatial distribution of climate change, most models agree that the changes will be largest at higher latitudes. However, there is a large degree of uncertainty for changes in precipitation, with models even disagreeing on what would be a sign of change in many regions (Meehl et al., 2007). This uncertainty in the spatial patterns of climate change can be taken into account by applying pattern scaling for temperature and precipitation based on a range of AOGCMs in IMAGE.

In addition to CO_2 concentrations and climate change, atmospheric composition is relevant in some IMAGE components. Air pollutants are used to calculate the effect on human health (Section 7.7). The effect of ozone on crop yields has been explored but is not yet part of the standard model set-up (Chuwah et al., submitted).

Limitations

Although coupling to an AOGCM is not workable for integrated assessments, some IAMs use an Earth System Model of intermediate complexity for climate modelling. This allows for more detail and consistency in climate change impacts and feedbacks, but is fixed to one representation of the system, not accounting for the large uncertainties. Using the simple climate model MAGICC 6.0 enables research on the consequences of parameter values outside current emulated AOGCMs. For example, the impact of high climate sensitivity values beyond the range found in AOGCMs (2 to 4.5 °C) can be studied (Müller et al., in prep.). This extends the range of uncertainty covered by the IMAGE model in projections of future climate change and the related impacts.

5. Key Publications

Meinshausen M, Raper SCB and Wigley TML. (2011a). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* 11(4), pp. 1417–1456, DOI: 10.5194/acp-11-1417-2011.

Müller C, Stehfest E, van Minnen JG, Strengers B, von Bloh W, Beusen A, Schaphoff S, Kram T and Lucht W. (in prep.). Reversal of the land biosphere carbon balance under climate and land-use change., *(available on request)*.

Van Vuuren DP and Stehfest E. (2013). If climate action becomes urgent: the importance of response times for various climate strategies. *Climatic Change* 121(3), pp. 473–486 DOI: 10.1007/s10584-013-0769-5.

6. Input/Output Table

Table 6.5.1
Input in and output from the climate model in IMAGE

Input	**Description**	**Source (section/ other)**
IMAGE model drivers and variables		
CO_2 emission from energy and industry	CO_2 emission from energy and industry.	5.2
Land-use CO_2 emissions - grid	Land-use CO_2 emissions from deforestation, wood harvest, agricultural harvest, bioenergy plantations and timber decay.	6.1
NEP (net ecosystem production) - grid	Net natural exchange of CO_2 between biosphere and atmosphere (NPP minus soil respiration), excluding human induced fluxes such as emissions due to deforestation and decay of wood products.	6.1
Non-CO_2 GHG emissions (CH_4, N_2O and Halocarbons)	Non-CO_2 GHG emissions (CH_4, N_2O, Halocarbons).	5.2
CO and NMVOC emissions	Emissions from CO and NMVOC.	5.2
BC, OC and NO_x emissions	Emissions of BC, OC, SO_2 and NO_x per year.	5.2
SO_2 emissions	SO_2 emissions, per source (e.g. fossil fuel burning, deforestation).	5.2
Cloudiness - grid	Percentage of cloudiness per month; assumed constant after the historical period.	6.5
Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period.	6.5

External datasets		
GCM pattern (temperature, precipitation) - grid	Climate change patterns of General Circulation models used to downscale changes in global mean temperature to changes in temperature and precipitation at grid level; default pattern from HadCM3 of the Hadley Centre.	IPCC-DDC (2007)
MAGICC parameter settings	MAGICC 6.0 parameters calibrated to emulate one out of 19 climate models.	Meinshausen et al. (2011c)
Radiative forcing factors	Radiative forcing per greenhouse gas.	Forster et al. (2007)
Sulphate pattern - grid	Patterns of climate change to compute non-linear regional radiative effects of sulphate aerosols.	Schlesinger et al. (2000)
Output	**Description**	**Use (section)**
Ocean carbon uptake	Ocean carbon uptake.	7.6
CO_2 concentration	Atmospheric CO_2 concentration.	6.1, 6.2
Non-CO_2 GHG concentrations	Atmospheric concentration of non-CO_2 greenhouse gases.	Final output
Radiative forcing	Radiative forcing of greenhouse gases, ozone, and aerosols.	Final output
Global mean temperature	Average global temperature.	7.2
Temperature - grid	Monthly average temperature.	6.1, 6.2, 6.3, 7.4, 7.5, 7.6, 7.7
Precipitation - grid	Monthly total precipitation.	6.1, 6.2, 6.3, 7.4, 7.5, 7.6, 7.7
Cloudiness - grid	Percentage of cloudiness per month; assumed constant after the historical period	6.1, 6.2, 7.6
Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period	6.1, 6.2, 7.5, 7.6

IMPACTS

IMPACTS

7 Impacts

7.1 Overview

Tom Kram

IMAGE 3.0 components for the Human system and Earth system are closely linked via multiple feedback mechanisms to form the core model of IMAGE 3.0. These components produce output for two types of purposes. One purpose is to serve as input for other IMAGE components and the other purpose is to serve as indicator for impacts. Many outputs serve both purposes, and many state variables of the IMAGE core components constitute interesting impact indicators, such as land-use change, crop yields and climate parameters.

The range of impacts has been extended beyond those that the core model can provide. As a result, additional impact components have been developed and linked to the IMAGE core model through static data exchange. These impact components can be used to address specific interests, and have been used in exploring a broad range of interactions between issues in sustainable development.

A wide range of impact indicators originate from the components in the core IMAGE model and those often reported in assessment studies are:
- Energy supplied, traded, converted and consumed (Section 4.1)
- Production of agricultural, animal and forestry products (Section 4.2.1)
- Forest cover, managed and unmanaged (Section 4.2.2)
- Agricultural land use and land systems (Section 4.2.3)
- Livestock numbers and feed, fodder and grass intake (Section 4.2.4)
- Land cover and land use (Section 5.1)
- Emission of greenhouse gases and air pollutants (Section 5)
- Biomass and carbon stocks and flows (Section 6.1)
- Potential and actual crop yields and grazing intensities (Section 6.2)
- Renewable water availability, irrigation and water stress (Section 6. 3)
- Nutrient balances and their fate in soils and surface waters (Section 6.4)
- Atmospheric concentration and radiative forcing of greenhouse gases and other forcing agents (Section 6.5)
- Global average temperature; temperature and precipitation changes per grid cell; sea level rise (Section 6.5)

Further impact components available in the IMAGE 3.0 framework include Terrestrial and Aquatic biodiversity, Flood risks, Soil degradation, Ecosystem services, and Human development. These components are presented in Sections 7.1 to 7.7.

7.2 Terrestrial biodiversity

Rob Alkemade, Michel Bakkenes, Johan Meijer, Ben ten Brink

Key policy issues

- What is the future rate of terrestrial biodiversity loss in the absence of additional policies and measures?
- What are the key pressure factors causing biodiversity loss?
- How will nature conservation policies and measures to reduce the key pressure factors of biodiversity loss contribute to meeting the targets of the UN Convention on Biological Diversity (CBD)?

1. Introduction

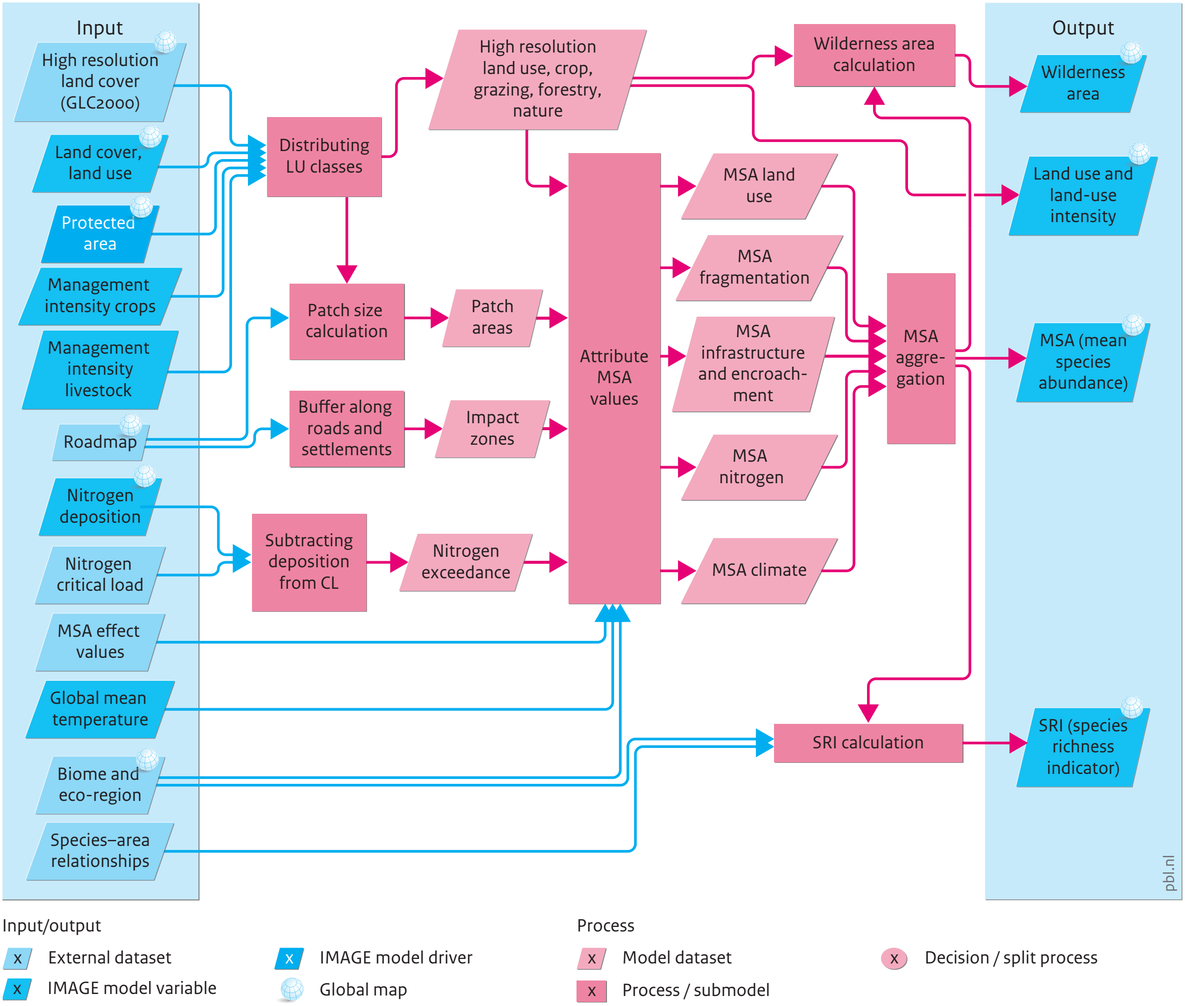
Biodiversity is declining rapidly with consequences for human well-being and ultimately even for the existence of humankind (MA, 2005). The Conference of Parties to the Convention on Biological Diversity (CBD) formulated the long-term vision: '*By 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people*'. For the period up to 2020, five strategic goals comprising 20 biodiversity targets have been adopted, referred to as the Aichi targets (sCBD, 2010).

IMAGE assesses the impacts of socio-economic drivers on the physical environment, such as climate change, land-use change and pollution, and these are input to the GLOBIO model to evaluate their impacts on biodiversity. GLOBIO was developed to provide information to policymakers at international level on current and future biodiversity, (Alkemade et al., 2009). The model delivers quantified results on the impact of environmental drivers and potential policy options on biodiversity. Potential trends in biodiversity are addressed in future scenarios, including the expected outcome in the absence of additional policies to prevent biodiversity loss.

GLOBIO builds on a series of cause–effect relationships between environmental drivers and biodiversity, based on state-of-the-art knowledge.

The key measure of biodiversity in GLOBIO is the mean abundance of original species relative to their abundance in undisturbed ecosystems. Referred to as the mean species abundance (MSA), this measure reflects the degree to which the ecosystem is intact and

Figure 7.2.1
GLOBIO model for terrestrial biodiversity in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.2.1).

is similar to the Biodiversity Intactness Index (Scholes and Biggs, 2005). New methods combine MSA estimates and species area relationships to estimate species loss at different geographical levels (Faith et al., 2008; Musters et al., submitted). The resulting Species Richness Index (SRI) is calculated as one of the end points of GLOBIO. The current version of SRI only covers vertebrate species. In addition, natural areas with high MSA values, defined as wilderness areas, are identified by their extent, landcover type and regional spread. The drivers of biodiversity loss considered are land-cover change, land-use intensity, fragmentation, climate change, atmospheric nitrogen deposition and infrastructural development.

2. Model description

The GLOBIO model calculates changes in biodiversity in terrestrial ecosystems, based on seven drivers of biodiversity change: land-use change, land-use intensity, climate change, atmospheric nitrogen deposition, infrastructural development, encroachment and fragmentation.

Four steps in the model are distinguished:
(i) Drivers of biodiversity change derived from IMAGE results are combined with additional data;
(ii) Mean Species Abundance (MSA) is calculated for each driver and year, using empirical relationships between driver and change in MSA (Alkemade et al., 2009);
(iii) MSA values for each driver are aggregated to obtain one MSA value;
(iv) Two additional indicators are calculated: Wilderness area, and Species Richness Index (Figure 7.2.1).

MSA expresses the relationship of mean species abundance between a disturbed or managed ecosystem and an undisturbed ecosystem, on a scale from 1 (undisturbed or pristine) to 0 (complete loss). This concept is applicable for most ecosystems and dynamics of biodiversity loss, and allows to compare and aggregate across ecosystems and drivers. However, it ignores possible increase in species abundance due to natural processes or in certain agricultural systems, such as European high nature value farmland.

Land use and land-use intensity
Changes in land use and land cover are major drivers of biodiversity change. Land use includes all human activities with a spatial component, such as forestry, agriculture, infrastructure and urban development. The impact of land use on biodiversity ranges from small (where the habitat quality is too poor for a limited subset of species) to large (where complete conversion of ecosystems results in habitat loss for a large number of species).

GLOBIO calculates maps of land-use categories and intensities for the year 2000. The starting point is land-cover data from GLC2000 (Bartholome et al., 2004) on the major types of forests, rangelands and agricultural land areas, at around 30 arc seconds resolution (1x1km near the equator). These data are combined with the World Database on Protected Areas (WDPA; (UNEP-WCMC, 2005) that distinguishes protected and non-protected areas. The land-cover classes obtained are summarised as proportions of cropland, forest and pasture for IMAGE grid cells of 5x5 minutes resolution.

For the period after 2000, changes in land use and land-use intensity from IMAGE are used as regional totals and allocated to the starting map. Data on cropland areas derived from the land-use allocation model (Section 4.2.3) are used as a total claim for each region. Three intensity classes are distinguished on the basis of management intensity (Section 4.2.3) for each region, calibrated with areas of irrigated, extensive and intensive croplands from the farming system typology from the FAO (Dixon et al., 2001). Data on three forestry management types are derived from the forest management module (Section 4.2.2), and data on two grazing intensities from the livestock module (Section 4.2.4).

The pastoral grassland areas are allocated in natural rangelands. Grazing in mixed systems is assumed on managed pastures, where the natural vegetation would be densely forested biomes. The remaining grassland areas (e.g., semi-arid and arid grasslands, tundra) are considered natural areas. All regional cropland, forests and grazing areas are geographically distributed per land-use intensity class by adjusting the proportion per grid cell, avoiding protected areas (Visconti et al., 2011).

MSA values for all land-use types are derived from the literature (Alkemade et al., 2009; Alkemade et al., 2012) and applied to the land-use map, with proportions of each land-use intensity class to yield the MSA land-use map for the year considered.

Climate

Climate is a key determinant of ecosystems and biodiversity. Climate change causes shifts in species occurrence and abundance, and ultimately may lead to local species extinction. Species distribution models (SDM) are used to describe relationships between climate variables and species distribution.

Regression equations are derived for each biome by applying a large number of SDMs to a series of climate scenarios, and calculating the proportion of remaining species per grid cell (0.5x0.5 degrees). The average proportion of remaining species per grid cell is related to the global mean temperature increase (GMTI) from IMAGE for the scenario considered (Alkemade et al., 2011a). The regression equation between GMTI and the proportion of remaining species is used to derive the map of MSA levels related to climate change for a given year.

Nitrogen

Nitrogen is a plant nutrient that stimulates growth, but some species benefit more than others and become more dominant with higher nitrogen availability. Thus, nitrogen deposition affects the species composition, mainly of plant and invertebrate species. Ecosystems can take up nitrogen without observable effects up to the level at which the assimilative capacity of the ecosystem is exceeded. This level of N input is defined as the critical load (CL).

Deposition rates of atmospheric nitrogen for current and future years are derived from IMAGE (Sections 5.2 and 6.4), and the map of critical loads is based on Bouwman et al. (2002b). The nitrogen exceedance is calculated by subtracting the critical load from the estimated deposition. For forested and grassland ecosystems, the MSA map for nitrogen is derived from the regression equation between nitrogen exceedance and the proportion of remaining species. Regression equations are derived from published impact studies on the effects of a nitrogen surplus on species composition (Bobbink et al., 2010).

Infrastructure and Encroachment

The construction and use of infrastructure, such as roads, railroads and built-up area, may have multiple impacts on biodiversity. Roads have a direct impact on species, for example as the result of traffic disturbance, road kills and habitat fragmentation (see below). There are also indirect impacts, such as increased human access to natural areas, increasing hunting, gathering and tourism. Traffic disturbance reduces the breeding success of bird and mammal species, reducing their abundance close to infrastructure. Hunting and gathering reduce populations when intensity exceeds threshold values.

Data on infrastructure are derived from the GRIP database resulting from the Global Roads Inventory Project (Meijer and Klein Goldewijk, 2009). Direct impacts occur in a 1000 m zone on both sides of roads and an MSA value is derived from a meta-analysis on disturbance effects (Benitez-Lopez et al., 2010).

Human settlements are the major access points to natural areas, and are likely to correlate with agricultural areas. Thus, 20 km impact zones are calculated around cropland areas and assigned as encroachment areas. Based on literature review of hunting activities, an MSA value of 0.7 is attributed to such zones. The MSA map for infrastructure and encroachment is obtained by combining the MSA map for direct (infrastructure) and indirect (encroachment) effects. In projections, the impact zone of direct effects is broadened according to the GLOBIO2.0 procedure (UNEP, 2001). Future impact zones for indirect effects are determined by the projections for agricultural areas.

Ecosystem fragmentation

Conversion of natural land to intensive cropping and road construction change vast areas of contiguous wilderness into a fragmented landscape with remnants of natural areas remaining as isolated islands. These relatively small patches are likely to house fewer species than could be expected from their habitat quality, because the individual patches may be too small to sustain viable populations of some species. Based on literature data on minimum area requirements of species, a relationship is constructed between patch size and relative number of species compared to a non-fragmented situation, known as the minimum area requirement (MAR) curve (Verboom et al., submitted). The relative number of species in a certain patch according to this MAR curve is used as a proxy for mean species abundance (MSA).

The area of natural vegetation patches is calculated by reclassifying the GLC2000 Global Land Cover data into two classes: human-dominated land (including croplands and urban areas) and natural land. Contiguous cells of natural land are grouped together and with an overlay of main roads (see above) are used to produce a map of natural land patches.

In scenario projections, patch sizes change as agricultural land use expands and as new roads emerge (Verboom et al., submitted). Changes in patch sizes also change the relative number of species and the MSA biodiversity indicator.

Aggregation

Total MSA values per area unit are calculated by multiplying the individual MSA values related to the separate drivers of biodiversity change (Figure 7.2.1) to arrive at the total effect of all drivers. The contribution of individual drivers to biodiversity loss is also calculated.

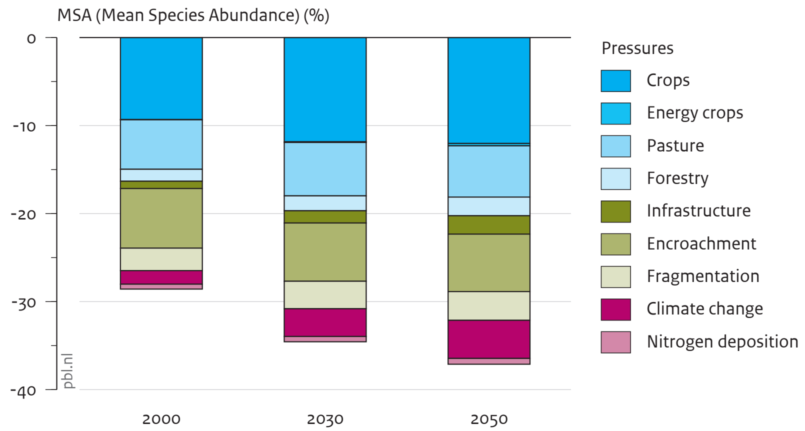
Wilderness areas are defined as natural areas with high (>0.8) MSA values. The Species Richness Index (SRI) is calculated by applying species–area relationships according to Faith et al. (2008), and using MSA values as a proxy for their intactness parameter. Aggregation from regional to global species richness is based on species lists in the Wildfinder database to avoid double counting (Musters et al., submitted).

3. Policy issues

Baseline developments

The GLOBIO model is used regularly to evaluate biodiversity impacts under baseline scenarios. Although the biodiversity decline depends on scenario assumptions, these studies all project decline in coming decades at a similar rate as in the previous decades. The main drivers of biodiversity loss are land-use change, infrastructure expansion and, increasingly, climate change (Figure 7.2.2).

Figure 7.2.2
Pressures driving global biodiversity loss under a baseline scenario



Source: PBL 2010

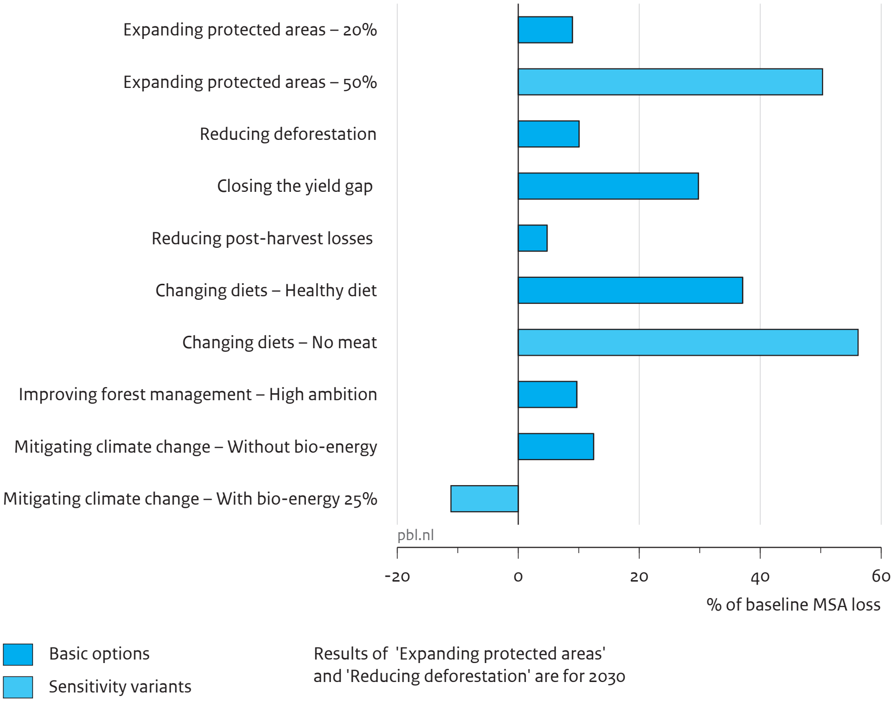
Land-use change and encroachment are projected to remain the most important drivers of biodiversity loss, but climate change will also become a significant pressure.

Policy interventions

Biodiversity loss is caused by a wide range of activities in various sectors, and policy interventions in major sectors could prevent or reduce biodiversity loss. The most often suggested option is protection of specific nature areas (reserves) to prevent further habitat loss for selected ecosystems. In addition, land pressure could be reduced, for example, by intensification of production, a shift in the human diet to fewer animal products, and waste reduction. The impact of climate change on biodiversity reduces with effective mitigation policies in place. Increase in sustainable forests may also reduce biodiversity loss in the long term.

The Rethinking Biodiversity Strategies study (PBL, 2010) evaluated a series of options (Figure 7.2.3) and shows that several options need to be introduced to significantly reduce biodiversity loss. Several interactions were found between these options. In some cases, the combined effect is smaller than if measures are taken individually. In other cases, synergistic effects were noted, for example, creating nature reserves may lead to higher crop prices, and in combination with yield improvements may prevent biodiversity loss without negative impact on crop prices. Analyses in Rethinking Biodiversity Strategies (PBL, 2010) and Rio+20 (PBL, 2012) also show that, up to 2030, further biodiversity loss cannot be prevented completely, but can be halted after 2030 with ambitious policy action.

Figure 7.2.3
Prevented global MSA (Mean Species Abundance) loss compared to baseline scenario, 2000 – 2050



Source: PBL 2010

Several policy interventions in land-use regulation, production and demand systems could prevent some of the biodiversity loss projected in the baseline. The single largest effects can be expected from closing the yield gap, and from dietary changes.

4. Data, uncertainties and limitations

Data

GLOBIO builds on data from literature reviews to construct relationships between biodiversity metrics (MSA) and environmental factors, such as land use, climate, and infrastructure. These are mainly local data on a large variety of ecosystems. Although systematically reviewed, representativeness is not guaranteed and bias may occur towards well-studied species groups, such as birds, and biodiversity-rich regions, such as tropical forests.

GLOBIO input used for assessing the impact of scenarios on biodiversity stems from various IMAGE components. This includes data on main drivers, such as land-use change (including cropland, grazing land and forests), climate change, and nitrogen deposition. Higher resolution data on land cover are derived from GLC2000 (Bartholomé et al., 2004), and data on infrastructure from the GRIP database (Meijer and Klein Goldewijk, 2009).

Uncertainties

Uncertainties in GLOBIO outcomes arise from parameterisation of cause–effect relationships, and uncertainties about the input data. Preliminary results from an ongoing sensitivity analysis indicate the largest uncertainties are about land use and land-use intensity parameters, even though these impacts are relatively well studied. In addition, the spatial resolution of land use and landscape composition is still rather coarse, and biodiversity patterns often strongly depend on small landscape elements.

Furthermore, the effect of climate change on biodiversity is based on a limited set of species distribution models and climate change scenarios. As the patterns of climate change are uncertain, and differ strongly between global climate models, the local impact of climate change on biodiversity is also subject to substantial uncertainty.

Limitations

Biodiversity is a complex concept that cannot be measured by a single indicator. CBD agreed on a set of five indicator categories to represent the state and changes in the state of biodiversity: extent of ecosystems; abundance and distribution of species; status of threatened species; genetic diversity; and coverage of protected areas (UNEP, 2004).

GLOBIO has indicators for species abundance (MSA), for the status of threatened species (SRI), and the natural and wilderness area is an indicator for the extent of relatively intact ecosystems. In principle, the GLOBIO model handles all ecosystems in the same way, reporting the relative reduction in MSA in relation to the natural state. Thus, the loss of natural area in a desert is awarded equal weight as the loss of a biodiversity hotspot in the tropics, although results can be presented per biome. This may be a controversial assumption, but there is no straight-forward method to weight ecosystems differently and it allows to assess a broad range of drivers and their effects on biodiversity in a consistent framework and on a global scale.

To broaden the scope of GLOBIO, additional aspects, such as information on ecological traits of the species in the GLOBIO database, are used to address genetic diversity (Newbold et al., 2013). A methodology for projecting Red List Indices is now being developed. The strength of GLOBIO is that a broad range of drivers and their effects on biodiversity can be assessed in a consistent framework and on a global scale.

5. Key publications

Alkemade R, Van Oorschot M, Miles L, Nellemann C, Bakkenes M and Ten Brink B. (2009). GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems* 12(3), pp. 374–390.

PBL (2010). Rethinking global biodiversity strategies, B. ten Brink, S. Van der Esch, T. Kram, M. Van Oorschot, R. Alkemade, R. Ahrens, M. Bakkenes, J. Bakkes, M. Van den Berg, V. Christensen, J. Janse, M. Jeuken, P. Lucas, T. Manders, H. Van Meijl, E. Stehfest, A. Tabeau, D. Van Vuuren and H. Wilting. PBL Netherlands Environmental Assessment Agency Bilthoven/The Hague, www.pbl.nl/en/publications/2010/Rethinking_Global_Biodiversity_Strategies.

6. Input/Output Table

Table 7.2.1
Input in and output from the terrestrial biodiversity model GLOBIO

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Protected area - grid	Map of protected nature areas, limiting use of this area.	3
Management intensity crops	Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions – current practice and technological change in agriculture – and is endogenously adapted in the agro-economic model.	4.2.1
Management intensity livestock	Management intensity of livestock, based current practice and technological change in livestock sectors, describing carcass weight and feed requirements of livestock.	4.2.1
Nitrogen deposition - grid	Deposition of nitrogen.	5.2
Global mean temperature	Average global temperature.	6.5
External datasets		
Biome and eco-region - grid	Biomes are groups of plants and animals, often referred as ecosystems. Their spatial distribution on Earth is defined by climatic and geographical conditions defined as contiguous areas with similar climatic conditions. Biomes are often referred to by climatic conditions (such as, tropical, temperate, boreal) and physiological characteristic (such as, grassland, deciduous trees, coniferous trees).	–

High resolution land cover (GLC2000) - grid	Land cover maps containing detailed, regionally optimised land cover classes for each continent, and a less detailed global classes harmonising across regional classes.	Bartholomé and Belward (2005)
MSA effect values	Database on empirical relationships between environmental pressures and reduction in mean species abundance for terrestrial ecosystems.	Alkemade et al. (2009)
Nitrogen critical load	Level of N deposition or concentration that should not be exceeded.	–
Infrastructure impact - grid	Impact zone grid derived from the GRIP database.	–
Species-area relationships	Number of species in relation to the size of an ecosystem.	Faith et al. (2008)
Output	**Description**	**Use (section)**
MSA (mean species abundance) - grid	Mean Species Abundance (MSA) relative to the natural state of original species.	5.1
Land use and land-use intensity - grid	High resolution land use and land use intensity based on GLC2000 and IMAGE land cover and land use.	7.6
SRI (species richness index) - grid	Species richness calculated from MSA and species area curves.	Final output
Wilderness area - grid	Non-agricultural areas close to their natural state, with MSA values above 0.8.	Final output

7.3 Aquatic biodiversity

Jan Janse, Rob Alkemade, Johan Meijer, Michel Jeuken

Key policy issues:

- How will the biodiversity in freshwater bodies develop in the absence of additional policies and measures?
- What are the key pressure factors causing loss of aquatic biodiversity?
- How will policies and measures to reduce the key pressure factors contribute to meeting the internationally agreed targets of the UN Convention on Biological Diversity (CBD)?

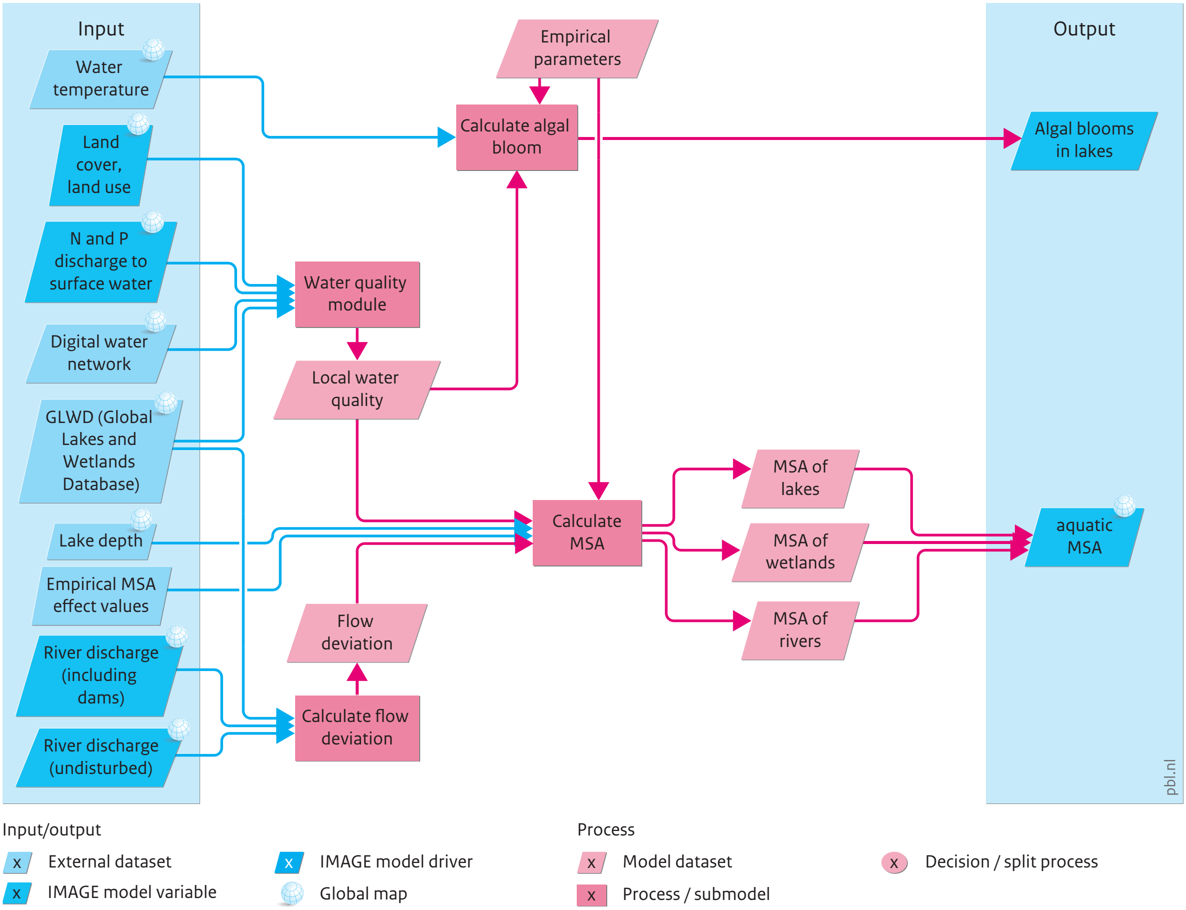
1. Introduction

Inland aquatic ecosystems, including rivers, natural lakes, reservoirs, and wetlands, cover about 8 to 9% of the Earth's continental surface (Lehner and Döll, 2004). The wetland area has declined considerably in the last century (Moser et al., 1998). Freshwater systems are dynamic and spatially interrelated , and the drivers of biodiversity loss partly differ from those of terrestrial ecosystems (see Section 7.2). Therefore, the effects of human-induced changes on the biodiversity of freshwater aquatic ecosystems is covered in a separate model in the IMAGE framework.

The GLOBIO model for aquatic ecosystems, GLOBIO aquatic, is based on a catchment approach to account for the composite effect of pressure factors on various parts of a catchment. The main drivers included are land use and nutrient loss within catchments, water flow deviations, and climate change. Changes in these drivers in future scenarios as calculated by the IMAGE model are used as input to GLOBIO aquatic.

The biodiversity indicators are comparable with those in the GLOBIO model for terrestrial ecosystems: species richness and biodiversity intactness, which is the mean abundance of original species relative to their abundance in undisturbed ecosystems (MSA). Similar to its terrestrial counterpart, the driver-impact-relationships for aquatic biodiversity are based on meta-analyses of empirical data from the literature. In addition to biodiversity indicators, the model calculates the occurrence of harmful algal blooms in lakes.

Figure 7.3.1
GLOBIO model for aquatic ecosystems



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.3.1).

2. Model description

GLOBIO aquatic assesses biodiversity intactness,expressed as mean species abundance (MSA) in inland aquatic ecosystems: rivers and streams, deep and shallow lakes and wetlands such as floodplain wetlands, marshes, and isolated wetlands. See Figure 7.3.1.

The model calculates the effects of land use changes in catchment areas in each of the aquatic ecosystems listed. For rivers and floodplain wetlands, the model also describes the effect of human interventions (e.g., through dam construction or climate change) on the hydrology on biodiversity. From a biodiversity perspective, reservoirs are considered as heavily modified river stretches. GLOBIO is also used to compute the probability of the dominance of harmful algal blooms of cyanobacteria (blue-green algae) in lakes, which often coincides with shifts in food webs and biodiversity loss, and which interferes with the human use of these systems.

The land-use effect on MSA in streams, rivers and wetlands is based on the type and proportion of human land use in the upstream catchment areas. Data from studies on biodiversity in rivers and streams in catchment and sub-catchment areas with different types of land use (e.g., forest, agriculture, urban) were combined in a meta-analysis. The data were expressed in MSA and fitted by linear regression (Weijters et al., 2009). A comparable meta-analysis was performed for wetlands (Janse et al., submitted). The analysis for lakes was based on phosphorus and nitrogen loadings, because the effects of eutrophication on lakes are well established, and nutrient loading to surface waters correlates closely with the type and intensity of land use (Harper, 1992; Bouwman et al., 2013c). Data from literature on the relationship between biodiversity and P and N concentrations were combined and fitted by logistic regression for deep and shallow lakes (Janse et al., submitted).

Local concentration levels are calculated from nutrient discharges to surface water (Section 6.4) and their accumulation and processing along the river network (see Section 6.3), currently using 0.5x0.5 degree resolution data. The model uses data on water bodies (streams, rivers, lakes, reservoirs and several types of wetlands) from the GLWD Global Lakes and Wetlands Database (Lehner and Döll, 2004) to calculate the proportion of each water body type in each grid cell. Lake depth categories were derived where possible from the Flake database (Kourzeneva, 2010).

The river network and GLWD map were combined in an overall water network map to estimate nutrient loadings to water bodies. Some wetland types are assumed to be isolated from the river network and thus only influenced by the land-use and nutrient emissions in the specific grid cell. An adapted wetland map can be used to take account of historical or projected wetland conversions to other land-use (Van Asselen et al., 2013).

For rivers and riverine wetlands, GLOBIO also considers the effect of hydrological changes on biodiversity. Monthly river discharges in pristine and in present or future situations (affected by climate change, dams and water abstraction) are derived from the hydrology module in LPJ model (Section 6.3). These monthly discharge patterns are used to calculate the deviation between affected and natural seasonal pattern, referred to as the Amended Annual Proportional Flow Deviation (Ladson and White, 1999; Biemans et al., 2011). Literature data on biodiversity in rivers under different regulation (e.g., by dams) were combined and expressed as a change in MSA (Janse et al., submitted). A comparable analysis was performed on the effects of flow deviation of biodiversity in riverine wetlands (Kuiper et al., submitted).

The MSA value for each water body (river, lake, wetland) is calculated by multiplying the values for the relevant drivers. The final indicator, aquatic MSA, is calculated by area-weighted averaging of MSA values for rivers, lakes and wetlands. In addition to MSA, the probability of dominance of harmful algal blooms of cyanobacteria in lakes is calculated as a biodiversity indicator, based on P concentration, N:P ratio, and water temperature (Håkanson et al., 2007). The results are expressed as the proportion of lakes with a cyanobacteria biomass above the WHO standard.

A more detailed description of the model is presented in (Alkemade et al., 2011b; Janse et al., submitted).

3. Policy issues

Baseline developments

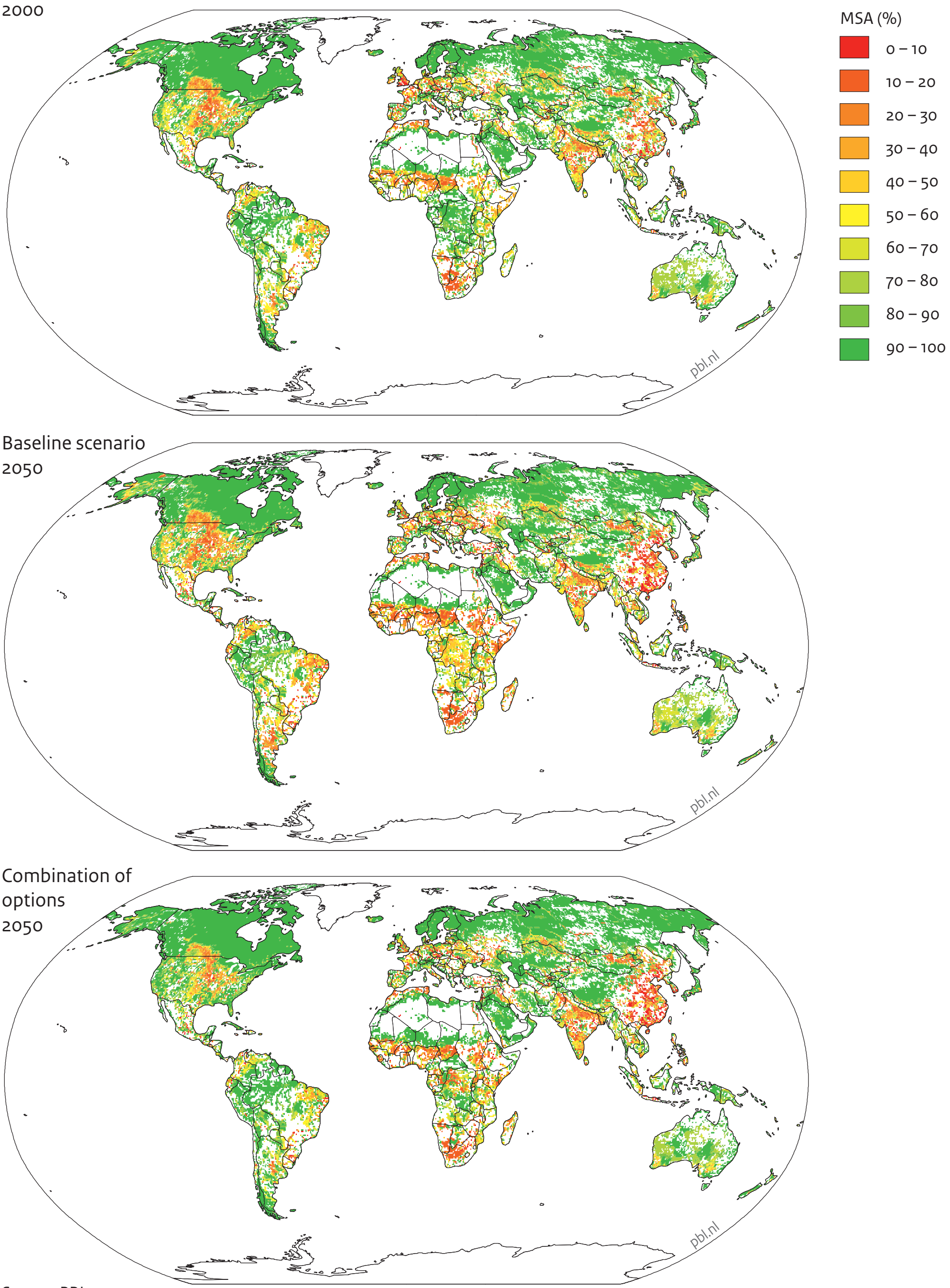
The GLOBIO model for aquatic ecosystems simulates average biodiversity intactness (MSA) in freshwater biomes under different baseline assumptions (assuming no new policies). Considerable decline in MSA is projected for most regions, and will continue throughout the 2010–2050 period, particularly in Africa (PBL, 2010; PBL, 2012); see Figure 7.3.2. The simulated declines are likely to be underestimated because the effects of wetland reclamation and future planned river dams and climate change have not yet been included in these projections. Algal bloom in lakes due to eutrophication with phosphorus and nitrogen will also increase.

Policy interventions

Decline in MSA value of future aquatic biodiversity can be prevented using a combination of options. These options include expansion of protected areas, reduction of agricultural area by means of consumption changes and reduced food losses, increase in agricultural productivity, and improved efficiency of nutrient use while reducing emissions. IMAGE calculations show this combination of options may even induce some recovery of biodiversity already lost in selected locations: increasing MSA), see

Figure 7.3.2

Aquatic Mean Species Abundance under a baseline scenario

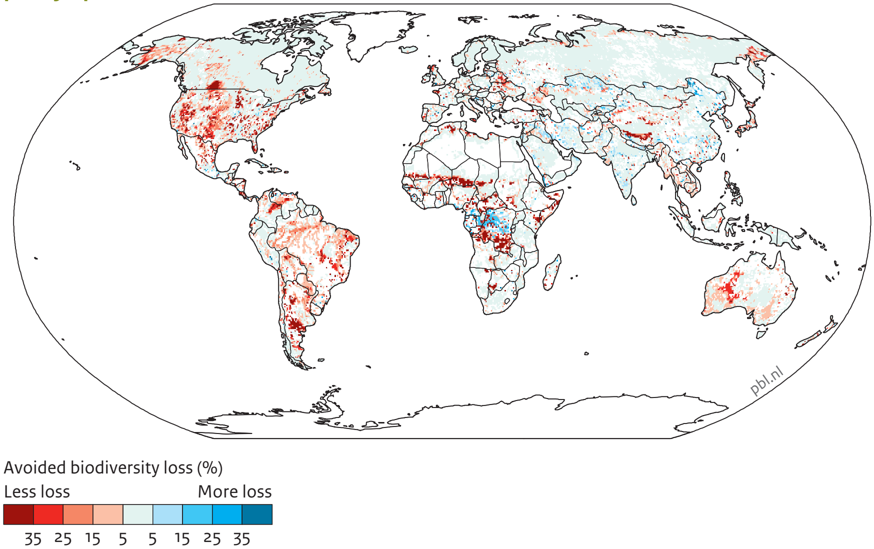


Source: PBL 2010

Under a baseline scenario, aquatic biodiversity is projected to decrease further.

Figure 7.3.3

Avoided aquatic biodiversity loss compared to the baseline, under a combination of policy options



Source: PBL 2014

A set of ambitious policy options could reduce aquatic biodiversity loss compared to a baseline scenario.

Figure 7.3.3). This may be counteracted by the effects of climate change (Mooij et al., 2005; Jeppesen et al., 2009). With respect to agricultural intensification, there may be a trade-off between increased biodiversity loss on local scale and decreased loss on catchment scale.

4. Data, uncertainty and limitations

Data

External data used in the model were derived from the global map of surface waters (Lehner and Döll, 2004), the lake depth database (Kourzeneva, 2010), and the map of dams and reservoirs (Lehner et al., 2011). All other input is generated by other IMAGE components. The empirical relationships between aquatic biodiversity and land use, nutrient budgets and hydrological changes, were derived from an extensive compilation of case studies on rivers, lakes and wetlands.

Uncertainties and limitations

A significant negative impact on biodiversity intactness was found for all types of inland aquatic ecosystems for these dominant categories of anthropogenic stressors. However, there are large variations in the data , and the effects partly depend on the characteristics of the study sites, taxonomic groups and other factors. There is a geographical bias towards well studied regions, and regions where both disturbed systems and comparable reference systems still exist, such as in North America, Australia and New Zealand, and to a lesser extent Europe.

Use of the model for other regions requires some caution, but is considered appropriate for large-scale assessments. The current approach is unique and innovative, because the impact of global environmental change on aquatic biodiversity can be simulated using pressure factors of land use and hydrological disturbance in a consistent global framework.

However, several other pressures are not yet represented in the system, although they may have impact on biodiversity, such as modifications to local rivers and basin morphology, exploitation (fisheries, aquaculture), invasive species, and toxic stress (Revenga et al., 2005). Possible interactions between factors have not yet been included. The rather rough schematisation of the routing network also limits the accuracy of the results.

5. Key publications

Alkemade R, Janse JH, Van Rooij W and Trisurat Y. (2011b). Applying GLOBIO at different geographical levels. In: Y. Trisurat, R. P. Shrestha and R. Alkemade (eds.), *Land Use, Climate change and biodiversity modeling: perspectives and applications*. IGI Global, Hershey (PA), pp. 150–170.

Janse JH, Kuiper JJ, Weijters MJ, Westerbeek EP, Jeuken MHJL, Alkemade R, Mooij WM and Verhoeven JTA. (submitted). GLOBIO-aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *(available on request)*.

6. Input/Output Table

Table 7.3.1
Input in and output from the aquatic biodiversity model GLOBIO

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
N and P discharge to surface water - grid	N and P discharge to surface water.	6.4
River discharge - grid	Average flow of water through each grid cell.	6.3
External datasets		
Digital water network - grid	Digital water network DDM30 describing drainage directions of surface water, with each cell only draining into one neighbouring cell, organising cells to river basins.	Döll and Lehner (2002)
Empirical MSA effect values	Database of empirical relationships between environmental pressures and reduction in mean species abundance for aquatic ecosystems.	Janse et al. (submitted)
GLWD (global lakes and wetlands database)	Global map of lakes and wetlands.	Lehner and Döll (2004)
Lake depth - grid	Database of lake depths.	Kourzeneva (2010)
Water temperature - grid	water temperature.	PCR-GLOBWB model
Output	**Description**	**Use (section)**
Harmful algal blooms in lakes	Harmful algal blooms in lakes caused by cyanobacteria, producing toxins harmful to humans and animals.	Final output
Aquatic MSA - grid	Relative Mean Species Abundance of original species in lakes, rivers and wetlands.	Final output

7.4 Flood Risks

Arno Bouwman and Hessel Winsemius

Key policy issues

- How will future flood risk change as a result of socio-economic and climatic changes?
- What would be the impact of floods, in terms of damage and victims, and where are the hot spots?
- What would be suitable adaptation strategies and investment options related to flood risk?

1. Introduction

Flooding is the most frequent and costly natural hazard that regularly affects many countries (UNISDR, 2011; IPCC, 2012). In the last few decades, economic damage as a result of flooding has increased in most regions, primarily due to growth in population and wealth in flood-prone areas (Bouwer et al., 2010; UNISDR, 2011; Barredo et al., 2012). In relative terms, economic loss and mortality from flooding are highest in developing countries, but lack of reliable and complete data remains an important issue for damage estimates.

To evaluate current flood risk and how the risks may change under future global change scenarios, rapid cost-effective assessments based on available global data are required. Such assessments are required, for instance, by international financing institutes to assess investment in risk reduction of natural disasters and by national institutes to monitor progress in risk reduction, such as under the Hyogo Framework for Action (UNISDR, 2005), by companies to justify insurance coverage and to assess risks to regional investments.

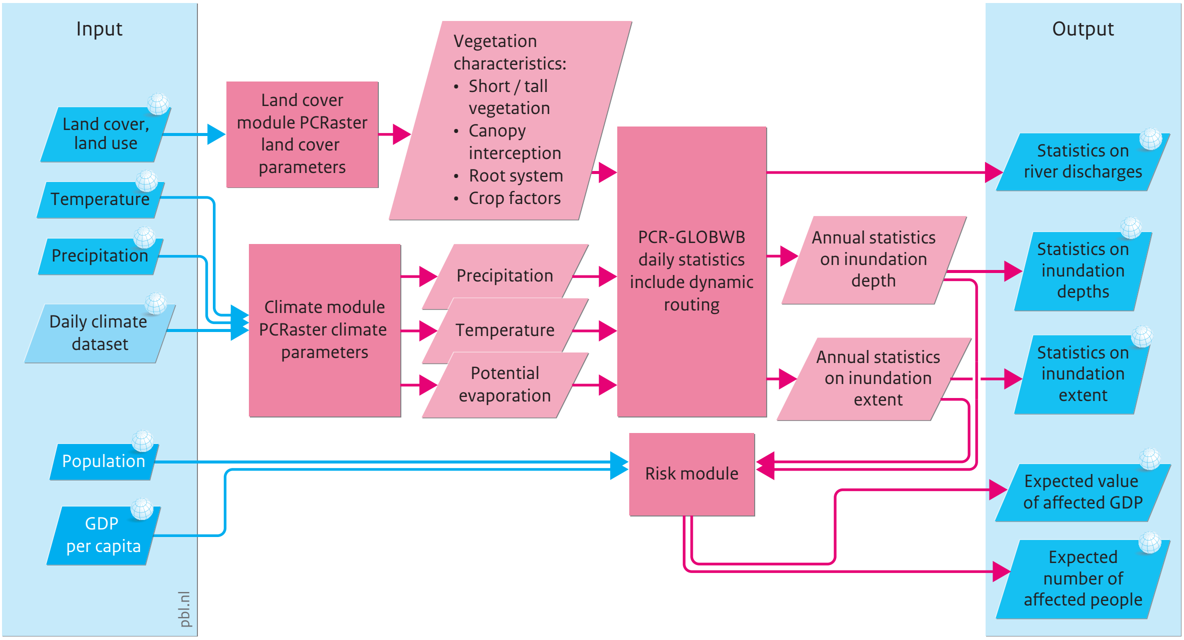
GLObal Flood Risks with IMAGE Scenarios (GLOFRIS) was developed for IMAGE 3.0 jointly by Deltares; PBL Netherlands Environmental Assessment Agency; Utrecht University; and the Institute for Environmental Studies, VU University Amsterdam. GLOFRIS estimates river and coastal flood risks by integrating the global hydrological model PCR-GLOBWB (Bierkens and Van Beek (2009) and the global sea-level rise impacts model DIVA (Hinkel and Klein, 2009), using climate scenario data from complex climate models and downscaled socio-economic scenarios from IMAGE.

GLOFRIS is used to assess current and future flood risks related to climate, changing land-cover patterns and changing socio-economic conditions in all world regions. This

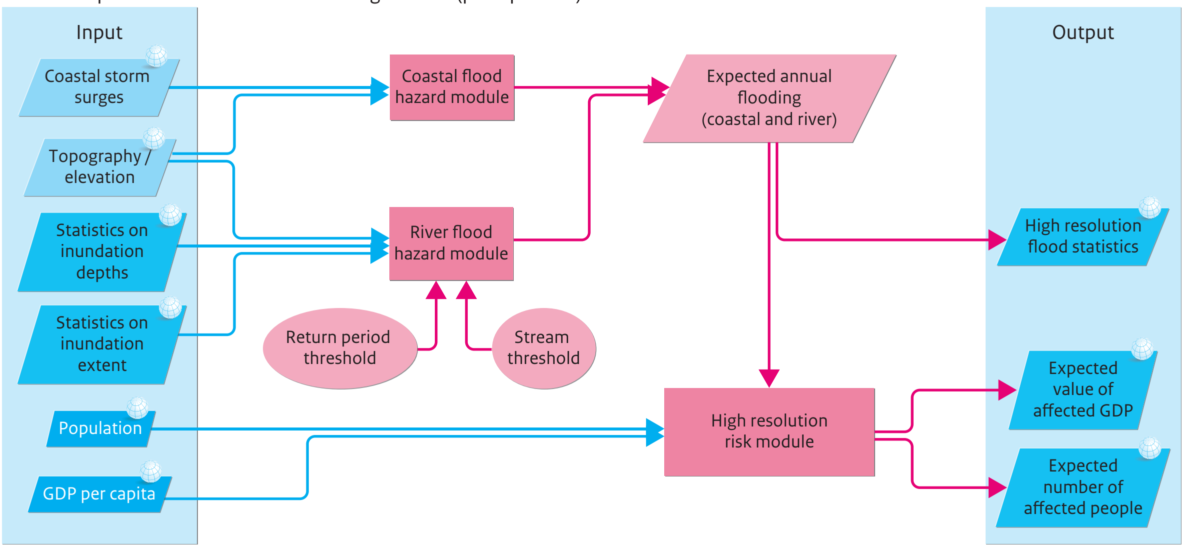
Figure 7.4.1

GLOFRIS, the flood risk model in IMAGE 3.0

Overview of the entire model



Detailed representation of the Downscaling module (post-process)



Input/output

- External dataset
- IMAGE model variable
- IMAGE model driver
- Global map

Process

- Model dataset
- Process / submodel
- Decision / split process

Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.4.1).

can be done globally at a resolution of 0.5x0.5 degrees and regionally at a higher resolution (1x1 km^2). The higher resolution is achieved using a specially developed downscaling algorithm and more detailed regional impact models. Impacts for various safety levels can be analysed. Possible applications include the preparation of IPCC scenarios for flood risk changes at 0.5 degree and 1 km^2 resolutions.

2. Model description

GLOFRIS estimates the effect of land cover and climate change on global flood risks in river catchments and coastal areas (Winsemius et al., 2012; Ward et al., 2013). Global flood risks are expressed as the projected number of people affected annually and as GDP value. GLOFRIS uses land-cover input from IMAGE and climate time series, such as the IPCC GCM projections. These input data drive the global hydrological model, PCR-GLOBWB, the computational core of the module. PCR-GLOBWB calculates where and when flooding events may occur, and calculates the inundation extent and inundation depth needed to estimate flood risks. PCR-GLOBWB has features, namely daily time steps and proper accounting of the relationship between non-linear soil moisture and run-off, that make it appropriate for simulating flooding events. The spatial resolution currently used by the model is 0.5x0.5 degrees. The model steps of GLOFRIS are shown in Figure 7.4.1.

Basis for the parameters in PCR-GLOBWB is the land-cover map Global Land Cover Characterization (GLCC), which express the hydrological characteristics of various land-cover types. IMAGE and PCR-GLOBWB are linked by lookup tables that translate the IMAGE land-cover classification into that of GLCC (Loveland et al., 2000).

PCR-GLOBWB requires data on daily precipitation, potential evaporation and temperature that are consistent with the IMAGE scenario (Van Beek et al., 2011; Wada et al., 2011). Daily data are required because these reflect inter-monthly and inter-annual climate variability and the effect on flood risk.

PCR-GLOBWB includes a routing component on river flooding that estimates inundation proportions and average inundation depths on a time-step basis to estimate flood risk. GLOFRIS scenarios typically cover a 30-year or longer climatological model run. From this time series, annual extreme values of the inundated proportions and water depths are derived and summarised in an extreme value probability distribution. This probability distribution is subsequently used for annual projections on the damage of flood risk.

GLOFRIS estimates flood risk on two scales 0.5x0.5 degrees for global analyses, and 1x1 km^2 for specific case studies. On a global scale, the extreme value probability distribution is directly combined with data on population and GDP, using a linear flood level–damage relationship. Thus for each year of simulation, the most extreme water level and inundated proportion from PCR-GLOBWB is used to calculate the maximum damage (in GDP or population) per grid cell.

An algorithm is implemented to scale down the 0.5x0.5 degrees maps of the extent and depth of annual maximum inundation to 1x1 km^2, using a high-resolution digital elevation model. A scale down is needed because the spatial variability of flood hazards and flood exposure may be large and not well represented on the coarser scales in IMAGE and PCR-GLOBWB. A more accurate estimation of flood risk is obtained by converting the results to a higher resolution. The downscaling procedure may also include the risk of coastal flooding (see Figure 7.4.1, bottom).

For scaling down in river catchments, annual extreme values of inundation depths and proportions are transformed to bank-full volumes and excess volumes per 0.5 degree cell. The bank-full volume represents the volumetric capacity of a river channel in a grid cell and is estimated according to flood volume in a user-defined return period in which flood volumes do not exceed the bank-full volume (return period threshold in Figure 7.4.1, bottom) under current climate and land-cover conditions. The excess bank-full volume for each year is scaled down by estimating a water level from identified river pixels. This is determined by the user-defined stream threshold (see Figure 7.4.1, bottom) that generates a flood volume in the surrounding connected pixels, resulting in the same flood volume estimated from the 0.5x0.5 degree results. The method is mass conservative with respect to the PCR-GLOBWB results on 0.5x0.5 degree cells.

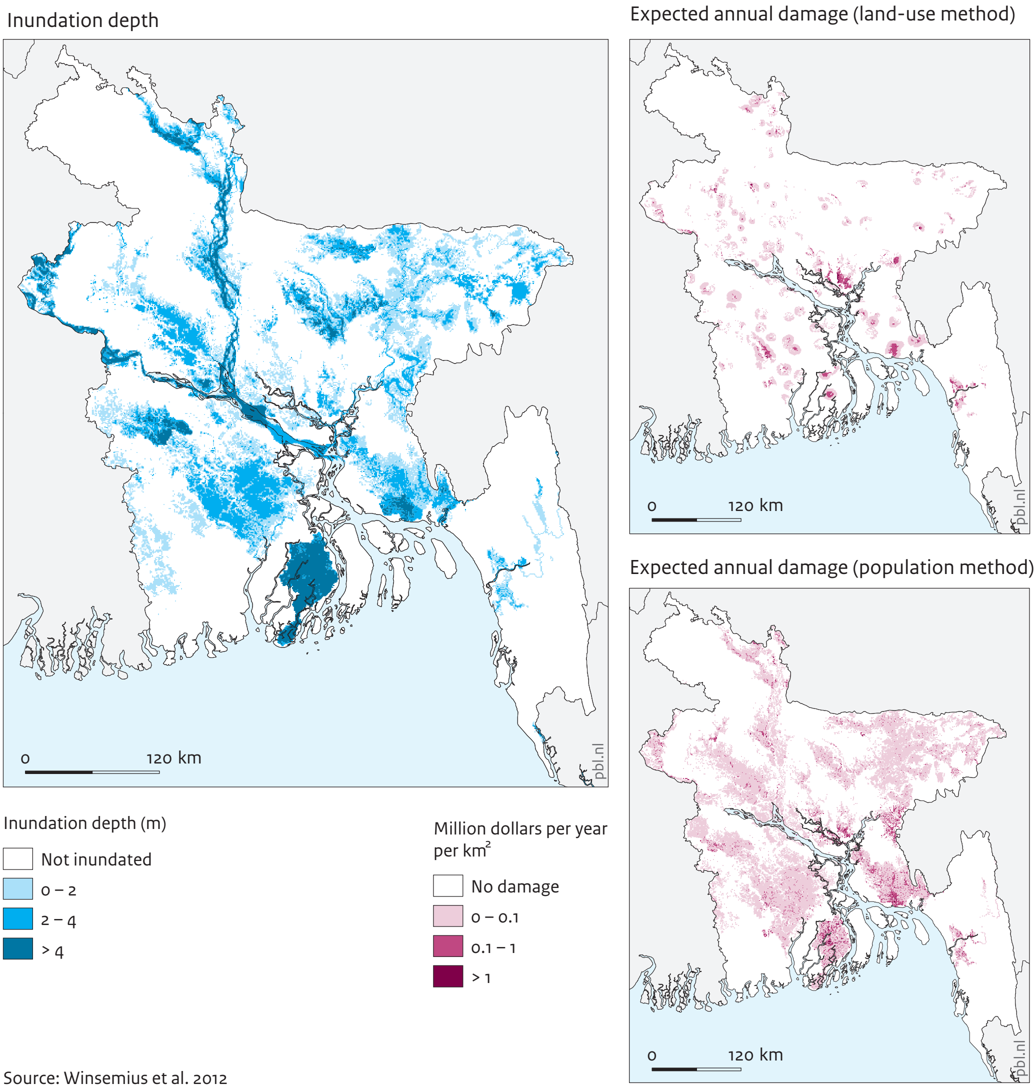
Coastal flood hazard maps are established using the DIVA database. DIVA contains estimates on 1-, 10-, 100- and 1000-year water levels along a large number of coasts worldwide (Hinkel and Klein, 2009). These coastal flood probabilities are combined with those on river flooding by finding the upstream connected pixels on the high-resolution elevation map that are lower than the coastal water levels. It is assumed that the height of a wave reduces as it moves inland and that the water spreads over the surface, resulting in lower water levels inland than on the coast.

After the high-resolution flood hazard maps have been established, the annual extreme values can be combined to form average annual flood hazard maps and flood risk maps. At this scale, more local detail can be added about cropland locations, high-resolution maps on population and GDP and other exposure data of interest. The resulting flood hazard maps can be combined with these high-resolution maps and, if possible, in more localised damage models.

More information about GLOFRIS, its underlying models and methods, and the downscaling module is available in Winsemius et al. (2012) and Ward et al. (2013).

Figure 7.4.2

Flood-related damage in Bangladesh, 30-year event, based on the historic climate (1961 – 1990)

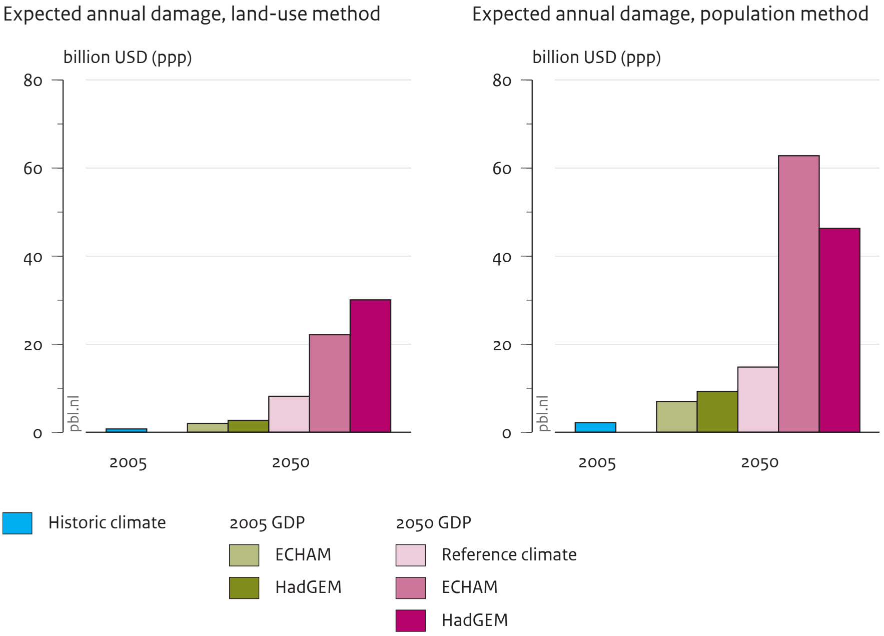


Source: Winsemius et al. 2012

Inundation depth of 30-year flood scaled down to Bangladesh (left); The estimated annual damage due to floods (not only due to a 30-year event) is more concentrated when applying the land-use method compared to the population method.

Figure 7.4.3

Flood related damage in Bangladesh



Source: Winsemius et al. 2012

Future expected annual damage due to flooding depends on future climate change, but much more on future GDP and population distribution.

3. Policy issues

Baseline developments

GLOFRIS can be used to assess a wide range of scenarios based on data on land cover and climate change. The module, for instance, has been used to analyse the impact of floods on Bangladesh published in Winsemius et al. (2012). Calculations showed that population and economic growth are more likely to have greater impact on future flood risks than the impacts of climate change. Thus, the focus would need to be on how the changes in socio-economic conditions can be combined with flood risk reduction.

The study compares the current situation with the impacts of changes in climate and socioeconomic conditions. The left panel in Figure 7.4.2 shows the pattern of a flood occurring once every 30 years according to GLOFRIS, scaled down to 1x1 km² over Bangladesh, under current climate conditions. The right-hand panels in Figure 7.4.2 show the resulting expected values of damage under current climate and socioeconomic conditions, based on the two methods described in Winsemius (2012). Flood risks have been computed using the two methods for the reference situation and for two climate data sets (Figure 7.4.3).

Policy interventions

To date, the model has not been used extensively for specific policy interventions. Measures taken elsewhere in the IMAGE framework to prevent climate change could also reduce flood risks.

4. Data, uncertainties and limitations

Data

Key external data used in the model are the digital elevation map, soil maps, initial land-use map, and a map of the global river network.

Uncertainties

The representativeness of the climate input is uncertain due to limited sampling length (generally 30 years or 100 years) and uncertainty in climate models. Thus, a multi-model ensemble of projections is highly recommended in preparing a scenario on future flood risk under a changed climate.

PCR-GLOBWB has uncertainties in its parameterisation of soils, vegetation, flood plain dimensions and roughness. These uncertainties are inherent to any hydrological model, and may be estimated using a multi-model ensemble built from runs with several hydrological models suitable for estimating flood hazards.

The downscaling algorithm is sensitive to the elevation model used and the choice of river and flood return periods (see also Winsemius et al., 2012; Ward et al., 2013). This uncertainty is particularly relevant when computing the flood risk of low return period events. Under high return periods, the bank-full volume becomes relatively small compared to the total flood volume and thus less important. The uncertainty of the chosen bank-full volume relates to the following uncertainty. In areas with high protection standards (e.g., against 100-, 500- or 1000-year floods), the simulated time series are likely to be too short to establish a satisfying probability distribution of events. Thus, the applicability of the framework to date has been limited to areas with low protection standards. This is the case in most developing countries

Limitations

Man-made interaction with river systems, such as the operation of dams and reservoirs, has not yet been taken into account. Instead, reservoirs are simulated as natural lakes with a free overflow. These could be included in future studies, but with the risk of incorrectly estimating reservoir operation during flood conditions. The impact of reservoir control could result in flood reduction provided adequate information is available to decide pre-releases. In many cases where such information is not available, the result may be larger floods due to unexpected water inflows. To date, reservoir management has not been considered in GLOFRIS.

The effect of levee breaches has not been included but can have large impacts on flood patterns. For example, during the Pakistan floods of 2009, large sections of a major embankment were destroyed by the floods, resulting in a completely different flood pattern than would be simulated by a model under the assumption of levee overtopping as the only flood mechanism. This type of flood mechanism requires a more interactive approach to mapping flood hazard that would allow for 'what if' scenarios on the schematisation of the elevation profile in a case study area. Such 'what if' scenarios are not suitable for a global approach as presented here.

Relatively simple stage-damage functions are used to estimate risks related to flood hazard and exposure. These functions vary greatly across the globe and may even represent the largest absolute uncertainty in our model results.

Flood risk is modelled as a function of flood hazard, exposure, and vulnerability, with vulnerability assumed to remain constant in time and space. However, future developments in resilience and adaptation measures may reduce vulnerability (e.g., due to increased awareness, other building methods or flood warning procedures).

5. Key publications

Winsemius HC, Van Beek LPH, Jongman B, Ward PJ and Bouwman AA. (2012). A framework for global river flood risk assessments. *Hydrology and Earth System Sciences Discussions* 9(8), pp. 9611–9659, DOI: 10.5194/hessd-9-9611-2012.

Ward PJ, Jongman B, Sperna Weiland F, A.A. Bouwman AA, van Beek LPH, Bierkens MFP, Ligtvoet W and Winsemius HC. (2013). Assessing flood risk at the global scale: model setup, results, and sensitivity. *Environmental Research Letters* 8, pp. 044019 DOI: 10.1088/1748-9326/8/4/044019.

6. Input/Output Table

Table 7.4.1
Input in and output from the flood risk model GLOFRIS

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	3
Population - grid	Number of people per gridcell (using downscaling).	3
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
External datasets		
Coastal storm surges	Estimates on storm surge/tide water levels for a large number of coast segments.	DIVA model (Hinkel and Klein, 2009)
Daily climate dataset - grid	Bias corrected daily precipitation, temperature and potential evaporation input.	EU-watch database
Flood statistics - grid	Annual statistics of water depth and the flooded fraction per grid cell.	–
Topography, elevation - grid	Global high resolution map of topography and elevation from NASA Shuttle Radar Topography Mission. Digital Elevation Model.	HydroSHEDS database
Output	**Description**	**Use (section)**
Statistics on inundation depth - grid	Annual statistics of water depth in flooded areas of a grid cell.	7.6
Statistics of inundation extent - grid	Annual statistics of flooded fraction per grid cell.	Final output
Statistics on river discharge - grid	Annual statistics on river discharge.	Final output
Expected nr of affected people - grid	Population expected to be exposed to floods per year.	Final output
Expected value of affected GDP - grid	GDP expected to be exposed to floods per year.	Final output

7.5 Land degradation

Michel Bakkenes, Ben ten Brink, Elke Stehfest, Tom Kram, Maurits van den Berg

Key policy issues

- In what parts of the world have human-induced changes in land and soil conditions occurred?
- What are the future risks of soil degradation?
- To what extent are ecosystem functions lost by soil degradation, adding to local and global concerns about food security, biodiversity loss and climate change?

1. Introduction

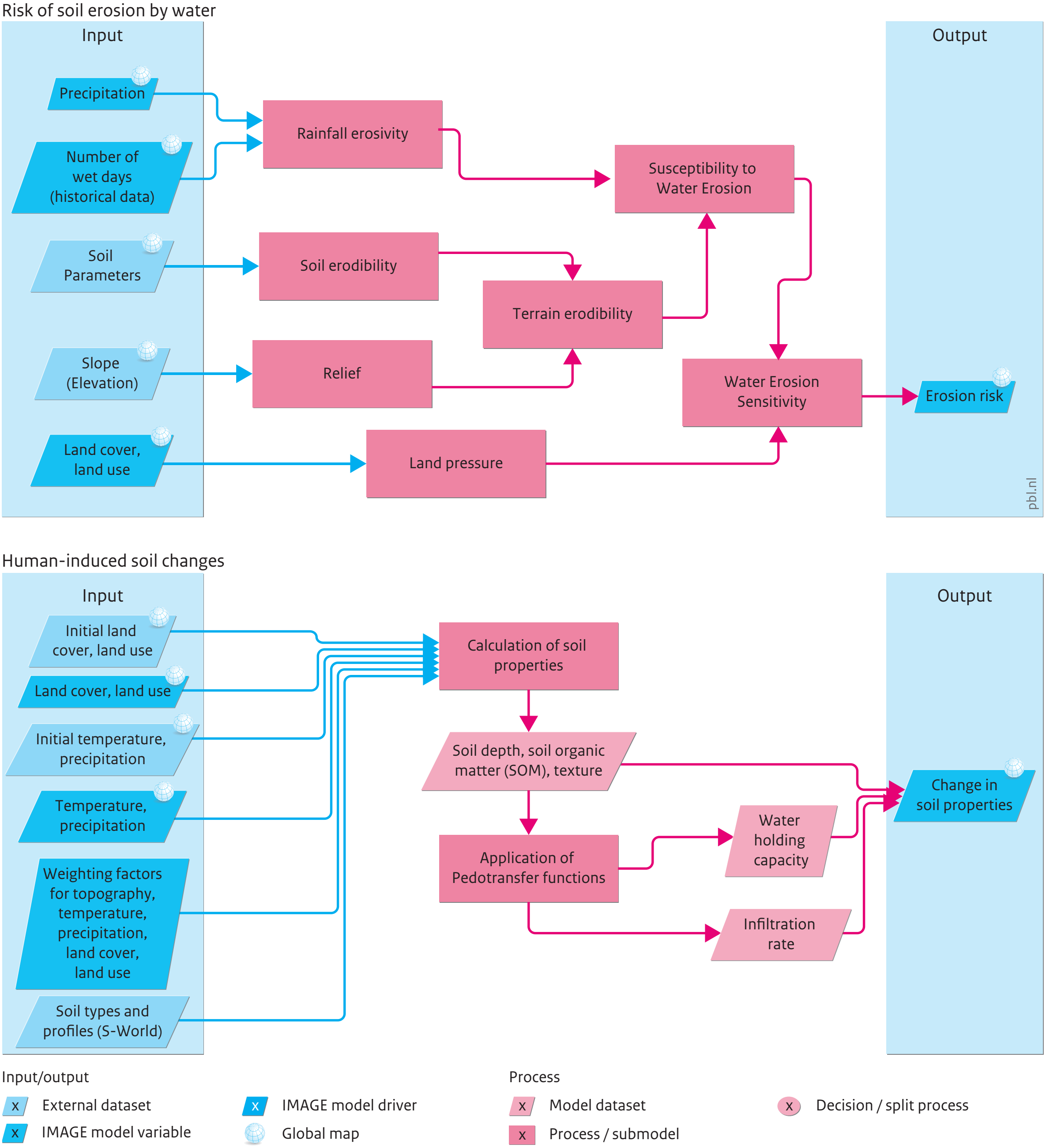
Land degradation is human-induced damage to ecosystems leading to a sustained loss of capacity. This is a serious and widespread problem leading ultimately to loss of arable land, and to demand for new arable land to compensate for decline in production on existing land. A key symptom of land degradation is loss of organic carbon from soils and vegetation, also contributing to global greenhouse gas emissions. The key mechanisms in land degradation are soil erosion (by water and wind), compaction, salinization, nutrient depletion, structural decay and contamination. The main causes are deforestation, land conversion, inadequate agricultural land use and management, and construction (urbanisation, road construction).

In 2012, the UN Convention to Combat Desertification (UNCCD) formulated the goal to achieve zero net land degradation as a Sustainable Development Goal for Rio+20 '*to secure the contribution of our planet's land and soil to sustainable development, including food security and poverty eradication*' (UNCCD, 2012). Land degradation is also relevant to the other Rio Conventions, with one of the Aichi targets of the Convention on Biological Diversity (CBD) aiming to restore at least 15% of degraded ecosystems.

While recognized as a global threat, the impacts of land degradation are poorly understood, and studies report differing results. For instance, productive soil loss equals 15 million km^2 according to Rozanov et al. (1990), while FAO reports about 43 million km^2 moderately to severely degraded land because of soil quality loss, water resource depletion and biodiversity loss (FAO, 2011). As a result, the impacts on productivity and economic losses with consequences for food security are also very uncertain. In the same way, the costs and benefits of investments to prevent land degradation and to restore degraded areas are also largely unknown (Nkonya et al., 2011). Many reasons for these discrepancies and knowledge gaps are identified

Figure 7.5.1

Two approaches to assess land degradation in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.5.1).

(Bindraban et al., 2012), including uncertainty about data, ambiguous definitions of land degradation, and methodology weaknesses in attributing changes in ecosystems to land degradation or to other causes.

Although a comprehensive model to capture the complex system interactions is not readily available, IMAGE 3.0 offers the following approaches to address soil degradation:

A. Water Erosion Risk: Risk assessment of soil erosion caused by water based on the Universal Soil Loss Equation (USLE; Wischmeier and Smith (1978)).

B. Change in soil properties: Quantitative assessment of changes in soil properties, from a hypothetically undisturbed (pristine) situation to a new situation, accounting for changes in land cover and other changes caused by human activity. The effect of changes in soil properties on crop production, hydrology and water can be assessed in other components of IMAGE.

2. Model description

A. Risk of soil erosion caused by water

Water erosion is the main cause of land degradation (1049 million hectares (Mha), followed by wind erosion (548 Mha), chemical degradation (239 Mha) and physical degradation (83 Mha) (GLASOD; Oldeman et al. (1991)). IMAGE assesses soil erosion by water (Hootsmans et al., 2001) by calculating a water erosion sensitivity index, ranging from zero (no erosion risk) to one (extremely high erosion risk). This risk is calculated for each grid cell as the compounded result of the following indices (Figure 7.5.1, top):

- *terrain erodibility index:* terrain erodibility represents the water erosion characteristics of the terrain in an index that combines surface relief and soil properties, expressed as index numbers. The **relief index** is a landform characteristic derived from a digital elevation model, calculated from the difference between minimum and maximum altitude in a 10 minute grid cell. The index is 1 for a difference of 300 m or more and zero for no altitude differences, with a linear relationship assumed between the two extremes. The **soil erodibility index** is derived from indices on soil texture, bulk density and soil depth. Soil characteristics were deduced from the 0.5x0.5 degree resolution in the WISE database (Batjes, 1997).
- *rainfall erosivity index:* this index represents exposure to heavy rainfall, derived from the month of the year with the highest precipitation and number of wet (rainy) days in each month. Rainfall erosivity is largely determined by the intensity of rainfall events, because soil loss only occurs during periods of intense rainfall. Monthly rainfall intensities of between 0 and 2 mm per day are assigned an index value of zero, and days exceeding 20 mm receive a value of one, with a linear relationship assumed between these two end points. Climate data are used for the historical period (Harris et al., 2013). For future years, predictions are based on changes in precipitation according to scenarios generated by the climate model, see Section 6.5. The number of wet days per month is assumed to be constant over time.

– *land-use/land-cover index:* this index presents the level of protection against water erosion offered by various types of natural vegetation and crops. The basis for this index is the geographic distribution of land-cover types generated by the land-cover model. Most types of natural vegetation provide a high degree of protection against water erosion, while agriculture, and arable agriculture in particular, increases the vulnerability of the soil surface. A composite value is used for grid cells that contain agriculture, based on the distribution of agricultural crops in that world region.

All intermediate and resulting factors are expressed as dimensionless indices from zero to one, and so too is the end indicator, Water Erosion Sensitivity Index.

The susceptibility and sensitivity indices are calculated according to:

$T = (Ia + SE)/2$

$Ep = (T+R)/2$

$WES = Ep \cdot V$

with:

Ia = relief index (-)
SE = soil erodibility index (-)
T = terrain erodibility index (-)
R = rainfall erosivity index (-)
Ep = water erosion susceptibility index (-)
V = land-use/land-cover index (-)
WES = Water Erosion Sensitivity Index (-)

Management systems are in use around the world to reduce the risk of erosion, such as building terraces, zero tillage, planting or conserving protective vegetation zones around fields, and high capacity drainage systems. The Water Erosion Sensitivity Index cannot capture all these and other interventions for the current situation, let alone into the future. The index only indicates areas potentially under threat. Impacts on crop production and soil quality cannot be derived directly from the indicator.

Comparison of the calculation above and the GLASOD degradation status maps by Oldeman et al. (1991) shows maximum correspondence with use of the classification in Table 7.5.2. This classification can be used as a guide in analysing the water erosion sensitivity indicator.

Table 7.5.2
Classification of the Water Erosion Sensitivity Index

Water Erosion Sensitivity Index	GLASOD soil degradation caused by water erosion
< 0.15	no/low
0.15 - 0.30	moderate
0.30 - 0.45	high
> 0.45	very high

B. Human-induced soil changes

Soil degradation is mostly reflected in changes in soil properties, such as soil depth, soil organic matter (SOM) content, and texture. Land cover and land use drive changes in soil properties. Land cover protects the soil against wind and water erosion, and provides organic matter to the soil. Land use tends to remove part of the biomass with harvested crops and residues and may increase mineralisation of SOM through tillage.

An empirical model S-World has been developed (Figure 7.5.1, bottom) that relates change in soil properties to topography, climate (average annual temperature and total annual precipitation), land management and land use, and land cover (as vegetation cover) (Stoorvogel, 2014; Stoorvogel et al., in prep.). The following soil properties are considered:

- topsoil depth,
- soil depth,
- soil organic matter in the topsoil and subsoil , and
- soil texture (sand and clay content).

S-World is based on the global Harmonised World Soil Database (HWSD; FAO et al., 2009) and the WISE soil profile database (Batjes, 2009). The compound mapping units in HWSD were disaggregated using detailed terrain information, so that each grid cell could be linked to a unique soil type described in the WISE database. For each soil type, ranges for the main soil characteristics described above were assessed on the basis of the WISE soil profiles. The range of variable, i.e., soil property v for every soil type s is subsequently defined as $[v_{ls}..v_{hs}]$ in which v_{ls} corresponds to the 1st decile and v_{hs} to the 9th decile. S-World downscales each soil property *v* based on 5 landscape properties or explanatory factors $[p_1, p_2 \dots p_5]$. These explanatory factors are temperature, precipitation, slope, land management and land cover. The land management is set to 1.0 for cropland, 0.5 for mosaics of cropland and pasture or natural vegetation, 0.3 for pasture, and 0.0 for natural vegetation; land cover is characterised by a remotely sensed NDVI map. The soil property *v* at location *x* with soil *s* is estimated as

$$\widehat{v_x} = v_{ls} + w_x * (v_{hs} - v_{ls}) \qquad (7.5.1)$$

with w_x being a weight $w \in [0..1]$ that determines where *v* is in the range $[v_{ls}..v_{hs}]$. Different explanatory factors represented by the landscape properties determine *w*. The weight at location *x* is calculated as $w_x = \sum_{p=1}^{5} w_{px}$. The weight w_{px} for landscape property *p* is calculated as:

$$c_{pv} \geq 0: w_{px} = c_{pv} * \frac{(p_x - p_{ls})}{(p_{hs} - p_{ls})} \qquad (7.5.2)$$

$$c_{pv} < 0: w_{px} = -c_{pv} \quad \frac{(p_{hs} - p_x)}{(p_{hs} - p_{ls})} \qquad (7.5.3)$$

In which c_{pv} is a constant that indicates the relative importance of the landscape property p for a soil property v. The sign of c_{pv} indicates whether there is a positive or negative relationship between the landscape property and the soil property. When $\sum_{p=1}^{n}|c_{pv}| = 1$, the $w \in$ [0..1] and all values in the range $[v_{ls}..v_{hs}]$ are possible based on the landscape properties. Although in practice c is specific for each landscape property, soil type, and soil property, data are lacking to estimate c at that level of specificity. Therefore the model assumes that c is constant per soil and landscape property, or, in other words, the relative impact of landscape properties on a specific soil property is assumed to be constant over the different soil types.

The soil properties are estimated based on land management and land use. This allows for the estimation of soil properties under pristine conditions. For future years, the NDVI map is changed as a function of land use, forest management and assumptions on degradation. To assess pristine conditions, soil properties are calculated with land use set at natural, and land cover represented by the NDVI under pristine conditions.

With this procedure, a change in soil properties (topsoil depth, soil depth, SOM in topsoil and subsoil, and soil texture) can be calculated as a result of land use and land cover. Subsequently, additional soil characteristics, such as water holding capacity and water infiltration rate, can be derived from these soil property values by using pedo-transfer functions (Van Beek, 2012). These soil characteristics can be used in other models in the IMAGE framework, such as LPJmL (Section 6.1) and GLOFRIS (Section 7.4), as alternative input to assess the consequences of historical or future land degradation.

3. Policy issues

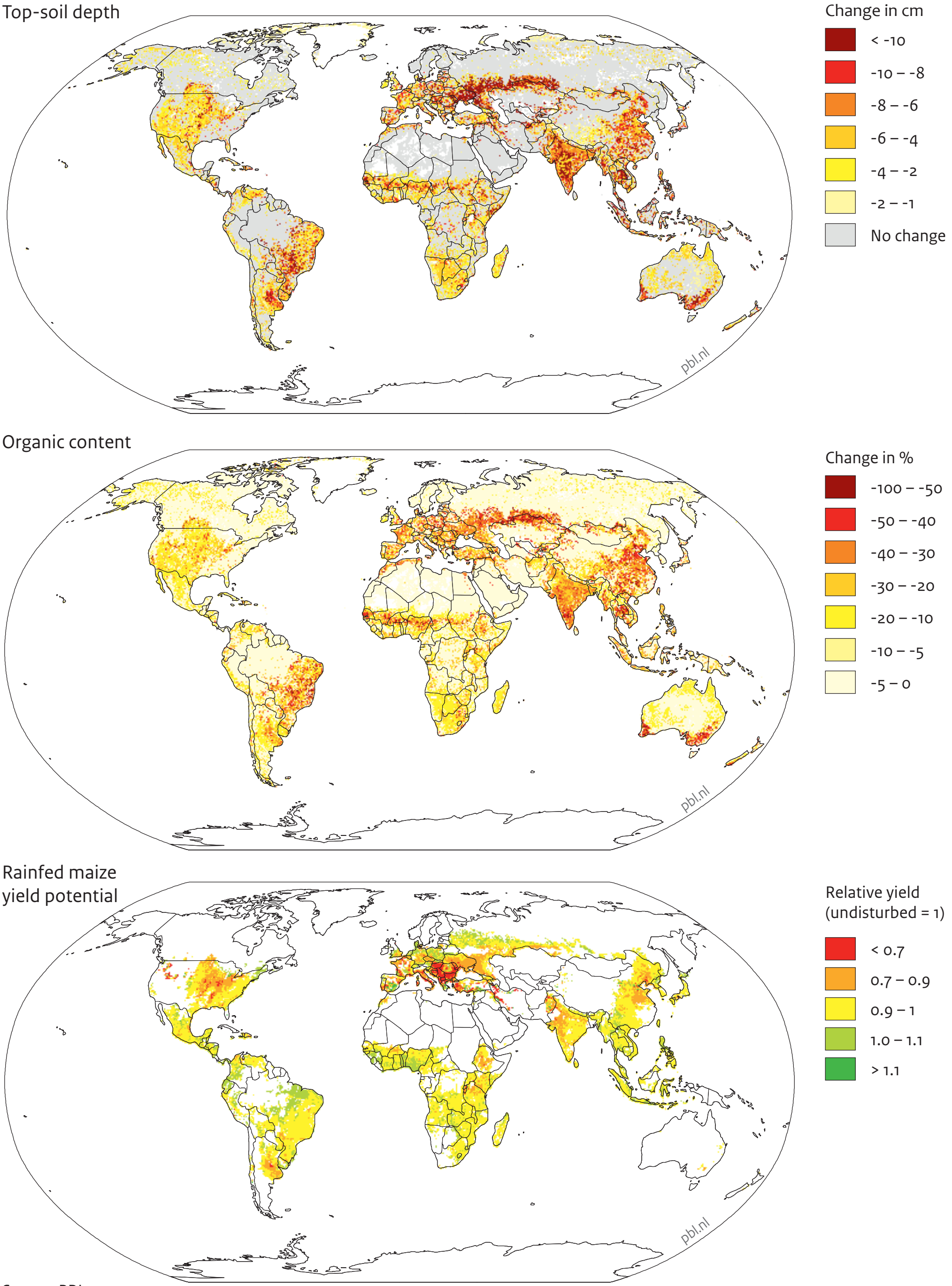
Baseline developments

The land degradation model in its current state is used to explore changes in degradation risk over time. Module A for Water Erosion Sensitivity is used to assess risks of soil erosion by water. Resulting maps are used to identify the most sensitive regions, and how areas under different risk categories change over time and space, subject to scenarios of future land use and climate change (Figure 7.5.3).

Module B for Human-Induced Soil Changes is used to estimate how historical land degradation propagates through the IMAGE 3.0 framework via change in topsoil depth, soil organic matter content and hydrologic soil properties. As a result of changing soil properties, agricultural productivity calculated by the LPJmL model can change (Figure 7.5.2). This module is used for future projections to assess the effect of climate change , land-use change, land cover change (as vegetation cover), and restoration activities on soil properties, and to study the impact of these changes on crop production, hydrology, and land-use dynamics.

Figure 7.5.2

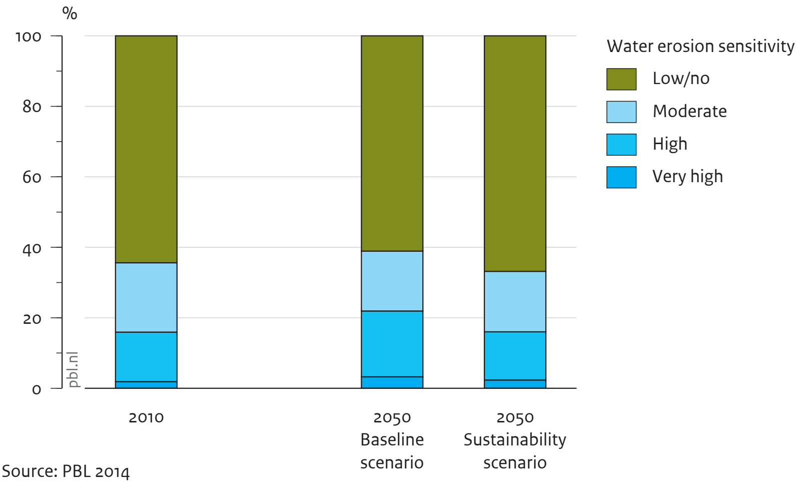
Change in main soil properties and maize yields, from undisturbed state to conditions in 2005



Source: PBL 2014

As a result of soil degradation and changes in soil properties, yields are up to 30 % lower than they would have been under pristine conditions, in some parts of the world.

Figure 7.5.3
Water erosion sensitivity of global land areas under baseline and sustainability scenario



Source: PBL 2014

Under baseline conditions, the risk of high and very high water-induced erosion increases strongly until 2050. Under the sustainability scenario (PBL, 2012), most of the increase under the baseline scenario is avoided by the combined effect of less land conversion and less climatic change.

Policy interventions

The modules on soil degradation are used in the IMAGE framework to calculate the impacts of changes in factors driving risks of degradation, such as changes in land use or climate. This is illustrated with the Rio+20 study by comparing the development of the Water Erosion Sensitivity Index under the baseline scenario with a sustainability scenario (Global technology). Areas characterised by high and very high risk increase strongly by 2050 with the development of land use and climate change under the baseline scenario by 33% and 69%, respectively, compared to 2010 levels (Figure 7.5.3). Under the Global Technology scenario, most of the increased risk is avoided because of less demand for agricultural land and reduction in climate change.

Both modules take into account climate change and land-use change and the effects on erosion risk and soil properties. The modules may be used to assess impact on the erosion risk of all policy interventions affecting climate and land use. However, the modules do not contain specific small-scale measures to reduce the degradation risks, such as reduced tillage and soil conservation practices. Future scenario studies could assess the aggregated effect of land-conservation-oriented policy interventions on the basis of more detailed relationships between agricultural practices and the land use intensity factor in module B.

4. Data, uncertainties and limitations

Both modules use the harmonised world soil database (HWSD), (FAO et al., 2009), and module B also uses the WISE soil profile database (Batjes, 2009), and the derived S-world database (Stoorvogel, 2014; Stoorvogel et al., in prep.). Although the HWSD and WISE databases are the most up-to-date sources of global soil data, they are still uncertain, especially for managed soils, and their base data have a rather course resolution.

Both modules are greatly simplified representations of land degradation and its potential impacts. For module A on Water Erosion, the largest uncertainty relates to the rather coarse resolution of the terrain erodibility, as small-scale terrain characteristics determine erodibility, but are not captured in global data sets. In addition, the intensities of rainfall events are very uncertain, and here are assumed to be only a function of monthly rainfall and number of wet days per month.

Methodologically, module B could be regarded as a better representation of the 'state of the art', because it makes full use of available data on a global scale. However, the module is completely based on the current state of the soil properties, and no account is taken of land-use history.

A major strength of module B on Human Induced Soil Changes is quantification of changes in soil properties. In combination with other IMAGE modules, these enable assessment of all types of direct and indirect impacts, a step forward from the common qualitative assessments of land degradation.

Soil degradation is strongly influenced by many aspects of land management and specific soil conservation management measures, which are not yet accounted for in the model. The module probably underestimates human-induced degradation, for several reasons: i) soil attributes remain compatible with the original soil type (soils are not allowed to change to such an extent that they fall into another class); ii) land-use change has an immediate effect and, in its present form, land management types in broad land-use categories are not accounted for; iii) some drivers of land degradation, such as salinization and nutrient depletion, are not taken into account.

5. Key Publications

Hootsmans RM, Bouwman AF, Leemans R and Kreileman GJJ (2001). Modelling land degradation in IMAGE 2. National Institute for Public Health and the Environment, Bilthoven, www.pbl.nl/en/publications/2001/Modelling_land_degradation_in_IMAGE_2

Stoorvogel JJ. (2014). S-world: A global map of soil properties for modeling. In: D. Arrouays, N. McKenzey, J. Hempel, A.C. Richer de Forges and A. McBratney (eds.), *GlobalSoilMap, basis of the global spatial soil information system*. Taylor & Francis Group, London, UK, pp. 227–231.
Stoorvogel JJ, Temme AJAM, Bakkenes M, Batjes NH and Brandsma J. (in prep.). A global soil property map for environmental modelling: S-world. (*available on request*).

6. Input/Output Table

Table 7.5.1
Input in and output from the land degradation module

Input	**Description**	**Source (section/ other)**
IMAGE model drivers and variables		
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period	6.5
Land cover, land use - grid	Multi-dimensional map describing all aspects of land cover and land use per grid cell, such as type of natural vegetation, crop and grass fraction, crop management, fertiliser and manure input, livestock density.	5.1
External datasets		
Slope - grid	Terrain slope index.	IIASA and FAO (2012)
Initial land cover, land use	Initial high resolution land cover and land use based on NDVI (Normalised Difference Vegetation Index).	GlobCover database
Initial temperature, precipitation	Global high resolution climate data from WorldClim.	WorldClim database
Land management	Land management index as a function of crop type	Hootsmans et al. (2001)
Soil types and profiles (S-World)	Soil profiles based on the HWSD (Harmonised World Soil Database) and on the ISRIC-WISE international soil profile dataset	S-World database (Stoorvogel et al., in prep.), HWSD database
Weighting factors for temperature, precipitation, land use and slope	Weighting factors for the contribution of temperature, precipitation, land use and slope on distribution of soil properties.	expert judgement, Stoorvogel et al. (in prep.)
Output	**Description**	**Use (section)**
Erosion risk - grid	Risk of soil erosion caused by water.	7.6
Change in soil properties - grid	Change in soil properties, such as clay/sand content, organic carbon content, soil depth (topsoil/subsoil).	5.1, 6.2

7.6 Ecosystem services

Rob Alkemade, Jennifer van Kolck, Nynke Schulp, Kees Klein Goldewijk, Michel Bakkenes

Key policy issues:

- How would ecosystem services and the benefits from the natural environment develop in the absence of specific policies?
- How could policy interventions contribute to improving future ecosystem services?
- How could policy interventions influence the interaction between ecosystem services and other goals and ambitions, such as the millennium development goals?

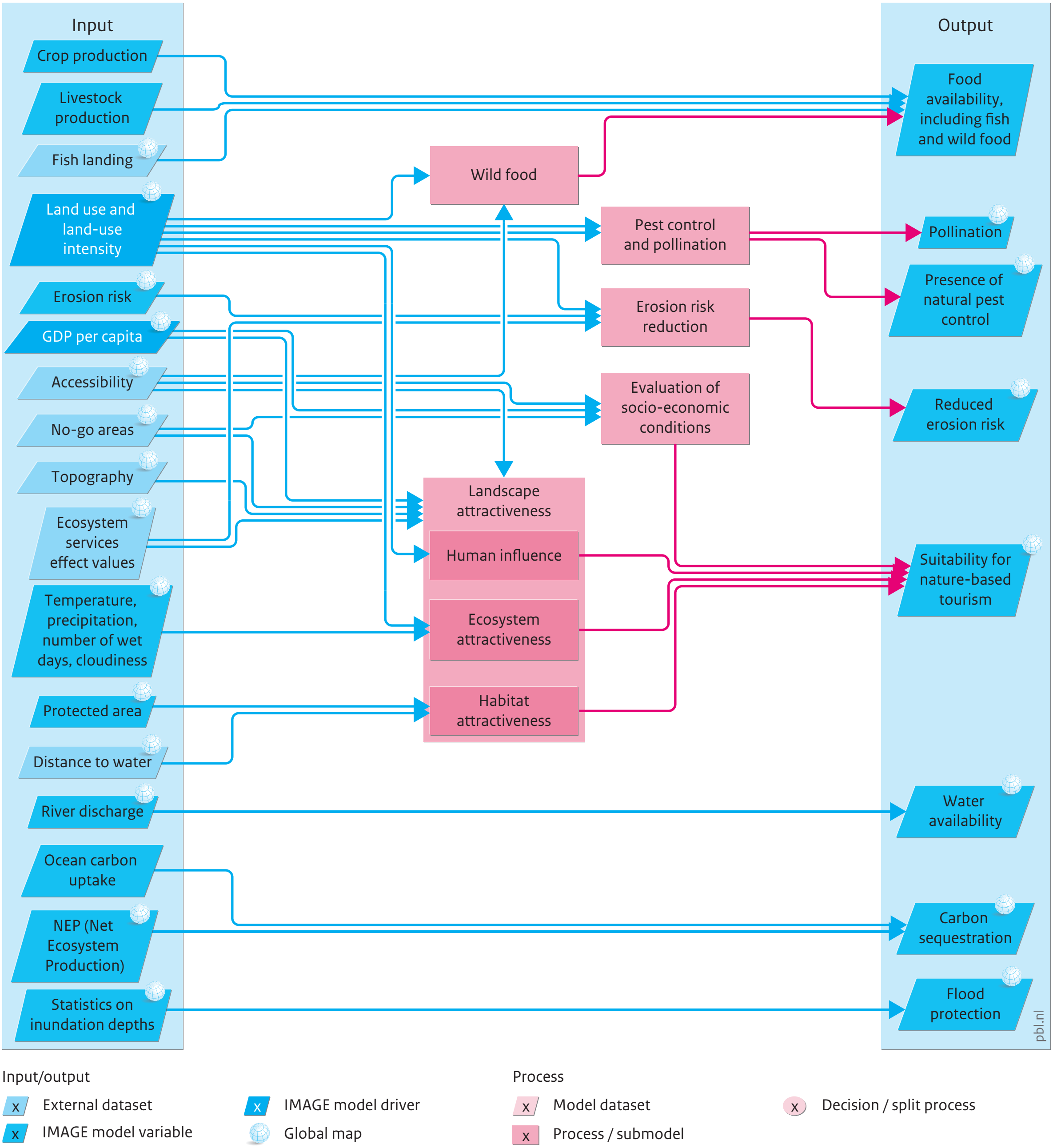
1. Introduction

Ecosystem services contribute to human well-being often in combination with other inputs (Burkhard et al., 2012). The identification and classification of the wide range of ecosystem services is still debated, but consensus is moving to the list of services published in the Millennium Ecosystem Assessment (MA), and further elaborated in the TEEB study and the CICES project (MA, 2005; TEEB, 2010b; De Groot et al., 2012; Haines-Young and Potschin, 2013):

- *Provisioning services*: goods and products obtained directly from the ecosystem, such as food, water and wood;
- *Regulating services:* benefits associated with physical processes influenced by the ecosystem, such as climate regulation and erosion control;
- *Cultural services:* non-material benefits to humans such as recreation;
- *Supporting services:* Processes assisting the supply of other ecosystem services, such as soil nutrient cycling supporting the provisioning of agricultural production.

Since the Millennium Ecosystem Assessment, the concept of ecosystems services has drawn increasing attention with many studies determining the influence on human well-being (Van Jaarsveld et al., 2005; TEEB, 2010b; TEEB, 2010a; Burkhard et al., 2012). For example, the TEEB study focused on the economic implications of the losses of a variety of ecosystem services , and other studies have tried to unravel the less tangible benefits of ecosystems to illustrate the importance of ecosystem conservation (Egoh et al., 2012; Bagstad et al., 2013; Garcia-Nieto et al., 2013).

Figure 7.6.1
Ecosystem Services model in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.6.1).

Understanding of ecosystem services is needed because pressures on ecosystems tend to increase as the world population grows and consumption patterns change. Unsustainable use and degradation of ecosystems may diminish delivery of services and may eventually impact on human well-being (MA, 2005; TEEB, 2010a; OECD, 2012). While food production, an ecosystem service itself, is increasing, it also puts pressure on other services, for instance forest conversion to agricultural land may result in decreasing supply of clean water, ecotourism, and flood and drought control (MA, 2005; Foley et al., 2011).

Growing concern about the unsustainable use has led to ecosystem services being incorporated in international and national policies. For example, the CBD Aichi targets endorsed by the EU biodiversity strategy address ecosystem services and the sustainable use of ecosystems (EC, 2012).

Ecosystem services are closely linked to the core focus of the IMAGE 3.0 framework to analyse interactions between human and natural systems (see Chapter 1). The eco-systems services module quantifies the supply of services, defined as functioning of ecosystems to produce services in a given time period. To quantify ecosystem services, a range of indicators is used from other IMAGE components , together with additional relationships developed to establish supply of services (Schulp et al., 2012). To identify deficiencies and surpluses in ecosystem services, the calculated supply is compared with the potential requirement for these services at an appropriate spatial scale.

2. Model description

The supply of ecosystem services is quantified using other components in the IMAGE 3.0 framework, and where necessary combined with relationships between environmental variables and ecosystem services supply, derived from literature reviews (Figure 7.6.1).

Ecosystem services derived directly from other IMAGE components include the food provision from agricultural systems; water availability; carbon sequestration; and flood protection. Estimation of the services, wild food provision, erosion risk reduction, pollination, pest control and attractiveness for nature-based tourism, requires additional environmental variables and relationships (Maes et al., 2012; Schulp et al., 2012). A key variable for these services is fine-scale land use intensity data from the GLOBIO model.

The supply of ecosystem services can be evaluated and aggregated in several ways. Some studies have constructed hotspot maps based on the number of services delivered (Egoh et al., 2008; Egoh et al., 2009; O’Farrell et al., 2010). Others translate service provision into monetary values for ecosystems (Costanza et al., 1997; TEEB, 2010b; UNEP-WCMC, 2011).

The main shortcoming of hotspot maps and monetising is the lack of information whether sufficient ecosystem services are delivered to fulfil human requirements (Burkhard et al., 2012). Here, the service supply is compared to the potential requirement (minimum quantity required by humans) in order to assess surpluses and deficiencies. This translates into minimum quantities of food and water to stay healthy, or the minimum quantity of natural elements in a landscape to potentially pollinate all crops. The relation between supply and potential requirement is the ecosystem services budget. These budgets are relevant at different spatial scales, because some services can only be provided locally, while others (mainly goods) can be transported longer distances. The most relevant assessment scale for each ecosystem service was determined given the underlying modelling approaches (Table 7.6.2).

Table 7.6.2
Assessment scale for each ecosystem service analysed

Category	Ecosystem service	Assessment scale
Provisioning services	Food from agro-ecosystems Wild food	IMAGE region Country, local market
	Fish Water Wood	Global River basin IMAGE region
Regulating services	Carbon sequestration	Global
	Erosion risk reduction	0.5°x0.5° grid
	Pollination	0.5°x0.5° grid
	Pest control	0.5°x0.5° grid
	Flood protection	30x30arcsec grid
Cultural services	Tourism	0.5°x0.5° grid

Provisioning services

Food

Food supply is broken down into three components: food produced on agricultural land (crops and livestock); fish from marine fish landings and aquaculture; and wild food from hunting and gathering. The food supply is converted to energy content (kcal nutritional value) and proteins (g) provided by the aggregate agricultural products, fish and wild food, and summed per IMAGE geographical region.

Agricultural ecosystems are modified by human interventions such as mechanisation, fertiliser application, irrigation, and agro-chemicals for pest and disease control. The degree of modification varies significantly between agricultural production systems, from slight in an extensive grazing system to heavy in modern agriculture. Even in the most heavily modified systems, the production of crops and livestock depends on ecological processes in agricultural ecosystems.

For crops and livestock products, data from the IMAGE crop and livestock module are used (Sections 4.2 and 6.4). Production volumes are modified for products used as feed and for post-harvest losses to estimate the food quantity consumed by humans. Marine fish landings per country are derived from the Sea around Us project (Sea around us project, 2013). The amount of fish derived from aquaculture is not yet included due to data limitations. Wild food can be an important part of local diets and includes game, mushrooms and berries. Local availability depends on the land cover and natural productivity of the ecosystem, and is determined from national and international hunting statistics for each land cover type (EFI, 2007; Schulp et al., 2012). Accessibility also influences availability of the wild food, and depends on the time people spend in collection including travel time (Nelson, 2008).

The potential food requirement is estimated by multiplying the minimum amount of energy and protein required per year on average to stay healthy (FAO, 2013b) and by the number of inhabitants per IMAGE geographic region

The budget is determined by subtracting the regional requirement from the total regional supply, indicating whether regional ecosystems supply sufficient food to meet the human requirement. The Ecosystem service 'food' relates to average numbers over a large population with very different standards of living, and access to affordable and healthy food. Therefore, even if total supply equals or exceeds demand, a larger or smaller proportion of the population in the region may suffer from malnutrition or hunger.

Water

Water availability is essential for natural vegetation, agricultural production, human settlements and industry. The renewable water supply is the water availability in a river basin and is derived from the IMAGE hydrology module (Section 6. 3). The water surplus of each grid cell is aggregated to watersheds to form river discharge. These flows are influenced by dams and reservoirs for irrigation and/or for hydropower production (Biemans et al., 2011).

The water requirement is also derived from the IMAGE hydrology module (Section 6.3), and is determined by adding together water use for agriculture (irrigation and livestock), industry, electricity and for domestic purposes in each river basin (Alcamo et al., 2003).

The budget is illustrated by the water stress in each river basin as the ratio of average annual water demand and supply (Vörösmarty et al., 2000). According to literature, medium water stress is indicated when >20% of the available water is extracted, and is considered severe when more than 40% of the available water is extracted. The ecosystem services 'water'is considered to be sufficiently supplied when there is less than medium water stress, below 20% extraction (Vörösmarty et al., 2000).

Regulating services

Carbon sequestration

CO_2 emissions are a key driver of climate change. By halting the increase of CO_2 concentration in the atmosphere, the consequences of global warming could be limited in the longer term. Natural vegetation and oceans can sequester CO_2 from the atmosphere and thus influence CO_2 concentration.

The amount of CO_2 sequestered by vegetation and oceans is considered an ecosystem service. A proxy for CO_2 sequestration by vegetation is net ecosystem production (NEP), which is the difference between net primary productivity (NPP) and plant and soil respiration. NEP values and ocean sequestration are adopted from IMAGE (Section 6.1 and 6.5). The supply values are averaged over ten years to account for year to year model fluctuation (Crossman et al., 2013).

Total CO_2 emissions from all sources would need to be sequestered to prevent increase in CO_2 concentration. Thus, the service requirement is the total CO_2 emissions from industry, energy and land use change (agriculture, deforestation and fires) from IMAGE, also averaged over ten years. The budget is established by subtracting emissions from CO_2 sequestered.

Erosion risk reduction

Erosion is the loss of topsoil by wind and water, and is a natural process. However, agricultural practices can accelerate erosion rates, reducing productivity and leading to loss of arable land. The model considers topsoil erosion related to water and agricultural practices (Section 7.5).

The erosion risk depends on topography, precipitation and agricultural practices, including crop type (see Section 7.5). The risk can be reduced by natural vegetation serving as buffer zones, erosion prevention strips and uphill soil retention cover. To determine the supply of ecosystem services, the erosion risk index from IMAGE is linearly reduced by the percentage of natural elements in a grid cell, derived from the land use and intensity map from GLOBIO (see Section 7.2).

Erosion prevention is needed in all cultivated areas. The ecosystem services budget indicates whether natural vegetation is sufficient to protect the area from erosion risk. According to (Hootsmans et al., 2001), an erosion index value greater than 0.15 indicates moderate erosion risk, and an index value in excess of 0.30 indicates high erosion risk. It is assumed the ecosystem services are adequate when the nature-corrected index value is below 0.15.

Pollination

Pollination is required for fruit setting for a large variety of oil crops, pulses and fruits. Pollinator-dependent crops require insects such as bees, bumblebees and flies, but also bats and birds (Gallai et al., 2009). To secure adequate pollination for such crops, sufficient habitat for wild pollinators is needed. The abundance of pollinators is shown to decrease with decreasing percentage of natural elements, which reduces the pollination efficiency and yield (Steffan-Dewenter and Tscharntke, 1999; Kleijn and Langevelde, 2006; Schulp et al., 2012).

The supply of this ecosystem service is derived from the relationship between the percentage of nature in a grid cell and the percentage of pollinator-dependent yield produced (Morandin et al., 2007; Klein et al., 2011; Schulp and Alkemade, 2011). Only yield produced by wild pollinators is included, but in practice yield is also influenced by managed- and self-pollination. When a grid cell contains 60% of nature, there are sufficient wild pollinators for all the plants and thus 100% of pollinator dependent yield is produced. However, when the percentage of nature decreases to 20% per grid cell, wild pollinators can still sustain 90% of pollinator-dependent yield. Less than 20% nature in a grid cell causes a sharp decline in yield (Morandin et al., 2007). Pollination is only needed in croplands, and we assume that in grid cells containing cropland and at least 20% of natural elements pollination is sufficient.

The budget is the cropland area with sufficient natural elements divided by the total cropland area.

Pest control

Natural pest control reduces pest occurrence in agriculture fields as a result of the presence of predator species (Thies et al., 2003; Boccaccio and Petacchi, 2009; Rusch et al., 2011). This leads to higher yields than in fields without natural or technical pest control. Natural pest control requires sufficient natural elements to house predator species close to agricultural fields. Pest control is assumed to be effective on agricultural fields within 2 km of forests and other natural elements (Bianchi et al., 2005). This can be translated into a correlation between the percentage of natural elements in a grid cell and the effectiveness of biological pest control (Thies et al., 2003; Boccaccio and Petacchi, 2009; Rusch et al., 2011).

Hawkins and Cornell (1994) indicate that natural pest control is no longer successful when the percentage of pest insects killed falls below 32 to 36%. This corresponds with 37 to 43% of nature in a grid cell. The model does not consider natural pest control by soil fauna present in the field.

The supply of natural pest control is determined by the percentage of nature in a grid cell. All cropland is assumed to potentially require effective natural pest control. The pest control budget is calculated by dividing the cropland area in cells with more than 40% of natural elements by the total cropland area.

Flood protection

Flooding is the most frequent and costly natural hazard, affecting most countries worldwide on a regular basis (UNISDR, 2011; IPCC, 2012). Therefore, flood risk assessment is an important issue for policymakers. While there are different levels of flood risk, the risk most often used by policymakers is the 100-year flood event which indicates a flood event occurring with a 1% likelihood in every year (Bell and Tobin, 2007). Protection against 100-year flood events, but not against less likely events, is considered a reasonable compromise between protecting the public and overly stringent regulation.

The flood risk is taken from the model GLOFRIS, which combines the flood extent and depth of river and coastal flood events, (Section 7.4).

Vegetation and soil affect inundation extent and depth because upstream vegetation can retain water and reduce flood risks. To calculate reduction in flood risk by ecosystems, flood risk is determined for a situation without conversion of natural vegetation and compared to flood risk in the current situation. The requirements for the service flood protection is estimated as the the depth of the 100-year flood event with the historical land use, vegetation and soil type.

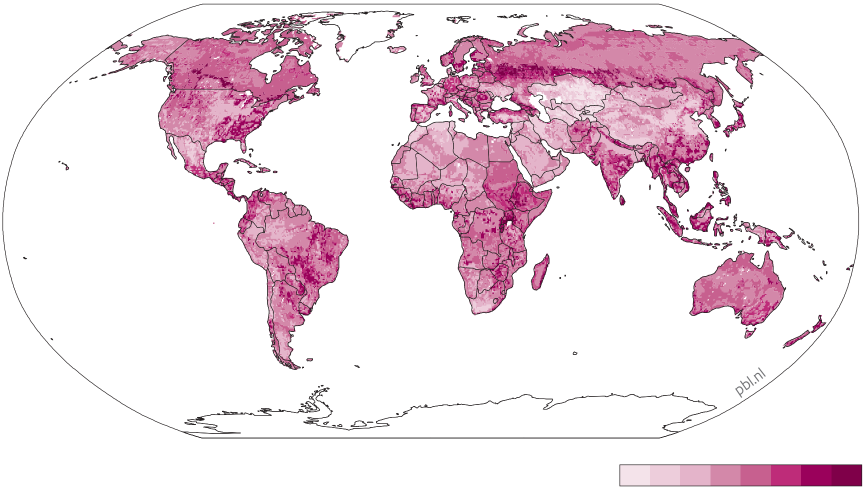
The budget illustrates whether change in vegetation and soil increases or decreases flood protection on urban and cultivated areas. Since the spatial variability of flood risk may be large, the 100-year flood event and the cultivated and urban areas are determined in 30x30 arcsec grid cells. The budget is aggregated to 0.5°x0.5° grid cell.

Cultural services

Nature-based tourism

The ecosystem service “nature-based tourism” is rather complex and there is limited knowledge about this service on a global scale. Drawing upon expert knowledge, we have listed several indicators influencing the supply of nature-based tourism (Van Kolck et al., in prep.). To be able to provide one single indicator for the ecosystem service supply, the indicators were grouped into three categories: an esthetic factor based on the climate-dependent tourism comfort index, scenic quality, land cover, and relief; a habitat factor based on distance to river, coasts, waterfalls and lakes, and the amount of protected area; and a deterrent factor based on extent of urban and cultivated area, accessibility, rate of traffic disturbances, GDP and safety. The three groups of indicators are normalized between 0-1 and summed to form one single supply indicator.

Figure 7.6.2
Number of the seven ecosystem services sufficiently supplied, 2000



Source: PBL 2014

Assessing how many of the 7 ecosystem services addressed in IMAGE (food, water, Carbon sequestration, erosion protection, pollination, pest control, flood protection, tourism) can be sufficiently supplied allows to identify hotspots of losses in ecosystem services.

In the absence of expert judgment, it was not possible to estimate a demand for nature based tourism. Hence, to indicate whether the ecosystem service supply meets a certain level, and to determine an ecosystem service budget, we have set an arbitrary threshold at 1.40. The budget is the area in grid cells with an index value above 1.40, divided by the total area.

Aggregation

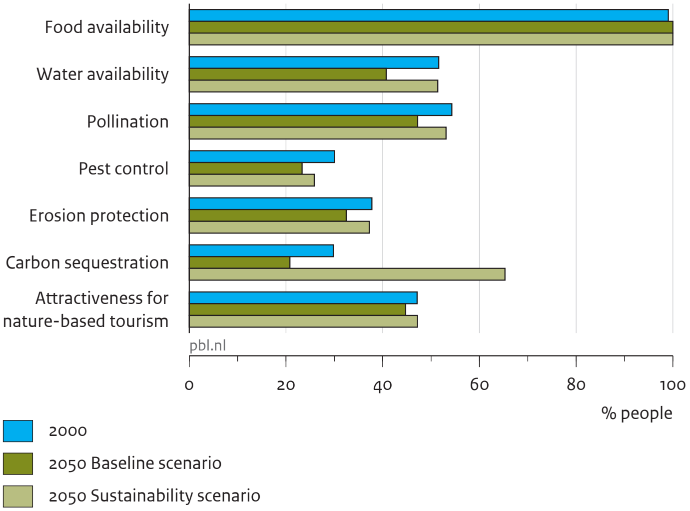
To aggregate ecosystem services, the budget of each service is set to a binary scale. Where zero indicates a service is not sufficiently delivered or not requested, and one indicates the supply meets the requirement, and thus is sufficiently delivered. These ecosystem service budgets on a binary scale can be summed to indicate the number of services sufficiently delivered in each grid cell.

3. Policy issues

Baseline developments

Around the world, the number of services (out of the seven services food, water, Carbon sequestration, erosion protection, pollination, pest control, flood protection, tourism) sufficiently supplied differs strongly (Figure 7.6.2)

Figure 7.6.3
Assessment of sufficient supply of ecosystem services under baseline and sustainability scenarios



Source: PBL 2014

While the supply of ecosystem services is decreasing under a baseline scenario, much of this decline could be avoided under a sustainability scenario (all based on PBL, 2012).

In a baseline, the proportion of people living in regions with sufficient supply of an ecosystem service is decreasing for most services in the future, except for food (Figure 7.6.3). According to the scenario, sufficient food will be produced regionally, but unequal food distribution will still lead to malnutrition and hunger. Areas with sufficient supplies of 'pest control, 'pollination' and 'erosion protection' are likely to decrease. Availability of water per person and the amount of carbon sequestrated relative to the amount emitted also decreases.

Policy interventions

As an example, the positive effect of one RIO+20 scenario (global technology scenario) on the sufficient delivery of most ecosystem services is presented in Figure 7.6.3. The percentage of sufficient delivery increases compared to the baseline in 2050. The sustainability scenario focuses on limiting climate change, which is also illustrated by sufficient delivery of carbon sequestration. The sharp decline in water in the baseline 2050 is prevented in the global technology scenario.

4. Data, uncertainties, and limitations

Data

Availability of data to relate land use and landscape characteristics to ecosystem services are still scarce and fragmented. For this reason, several services are represented by parameters from the IMAGE core module without modification, such as crop and livestock production, water availability, carbon sequestration, erosion risk, and flood risk.

For other services, additional relationships were developed. These relationships, for example for pollination and pest control, are based on a limited number of studies.

Uncertainties and limitations

To determine ecosystems services on a global scale, global land cover maps are used. These maps illustrate the spatial distribution of land cover, but the coarse resolution means that small landscape elements and minor land cover types are poorly represented (Schulp and Alkemade, 2011). In the relatively large grid cells used in this module, the major land cover types dominate minor land cover types. Especially linear landscape elements, such as ditch banks and tree rows, disappear because of aggregation of land cover data (Moody and Woodcock, 1996).

This geometric uncertainty influences many ecosystem services because many are influenced by the land cover type. This is the case with pollination, pest control and erosion because they are heavily influenced by linear landscape elements. This uncertainty may lead to underestimation of the supply of pollination, pest control, and erosion.

5. Key publications

Schulp CJE, Alkemade R, Klein Goldewijk K and Petz K. (2012). Mapping and modelling ecosystem functions and services in Eastern Europe. *Journal of Biodiversity Science, Ecosystem Services and Management* 8(1-2), pp. 156–168, DOI: 10.1080/21513732.2011.645880.

Van Kolck JGH, Ten Brink B, Alkemade R, Kram T, Schulp CJE, Amelung B and Bakkenes M. (in prep.). The difference between 2000 and 2050: quantifying and mapping the supply and demand of seven ecosystem services on a global scale. *(available on request)*.

6. Input/Output Table

Table 7.6.1
Input in and output from the ecosystem services module of IMAGE

Input	Description	Source (section/other)
IMAGE model drivers and variables		
Protected area - grid	Map of protected nature areas, limiting use of this area.	3
GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	3
Temperature - grid	Monthly average temperature.	6.5
Precipitation - grid	Monthly total precipitation.	6.5
Number of wet days - grid	Number of days with a rain event, per month; assumed constant after the historical period	6.5
Cloudiness - grid	Percentage of cloudiness per month; assumed constant after the historical period	6.5
Ocean carbon uptake	Ocean carbon uptake.	6.5
NEP (net ecosystem production) - grid	Net natural exchange of CO_2 between biosphere and atmosphere (NPP minus soil respiration), excluding human induced fluxes such as emissions due to deforestation and decay of wood products.	6.1
Erosion risk - grid	Risk of soil erosion caused by water.	7.5
River discharge - grid	Average flow of water through each grid cell.	6.3
Statistics on inundation depth - grid	Annual statistics of water depth in flooded areas of a grid cell.	7.4
Crop production	Regional production per crop.	4.2.1
Land use and land-use intensity - grid	High resolution land use and land use intensity based on GLC2000 and IMAGE land cover and land use.	7.2
Livestock production	Production of livestock products (dairy, beef, sheep and goats, pigs, poultry).	4.2.1
External datasets		
Topography - grid	Topography and altitude, determining the altitude range within a grid cell.	GLOBE Digital Elevation Model
Accessibility - grid	Accessibility expressed as travel time.	Nelson (2008)
Distance to water - grid	Distance to water.	based on HYDRO1K, GTOPO30 DEM, coastline map
Fish landing - grid	Fish landings according to statistics from "Sea around us".	Sea around us project (2013)
No-go areas - grid	Areas not recommended for tourists due to war, high poverty rates or poor safety conditions.	The World Bank, World development indicators
Ecosystem services effect values - grid	Database on relationships between environmental factors and ecosystem services.	

Output	Description	Use (section)
Food availability, including fish and wild food	Food availability, including fish and wild food.	Final output
Water availability - grid	Water availability in rivers, lakes and reservoirs.	Final output
Carbon sequestration - grid	net carbon uptake by terrestrial ecosystems and oceans	Final output
Reduced erosion risk - grid	Reduction in erosion risk by natural vegetation.	Final output
Pollination - grid	Additional yield due to natural pollination.	Final output
Presence of natural pest control - grid	Presence of natural pest control.	Final output
Flood protection - grid	Reduction in flood risk by natural vegetation.	Final output
Suitability for nature-based tourism - grid	Attractiveness for nature-based tourism.	Final output

7.7 Human development

Paul Lucas and Henk Hilderink

Key policy issues

- What are the key future trends in human development, such as those targeted by the Millennium Development Goals (MDGs)?
- How are changes in the global environment likely to affect human development?
- How is improved access to food, water and energy likely to contribute to human development?

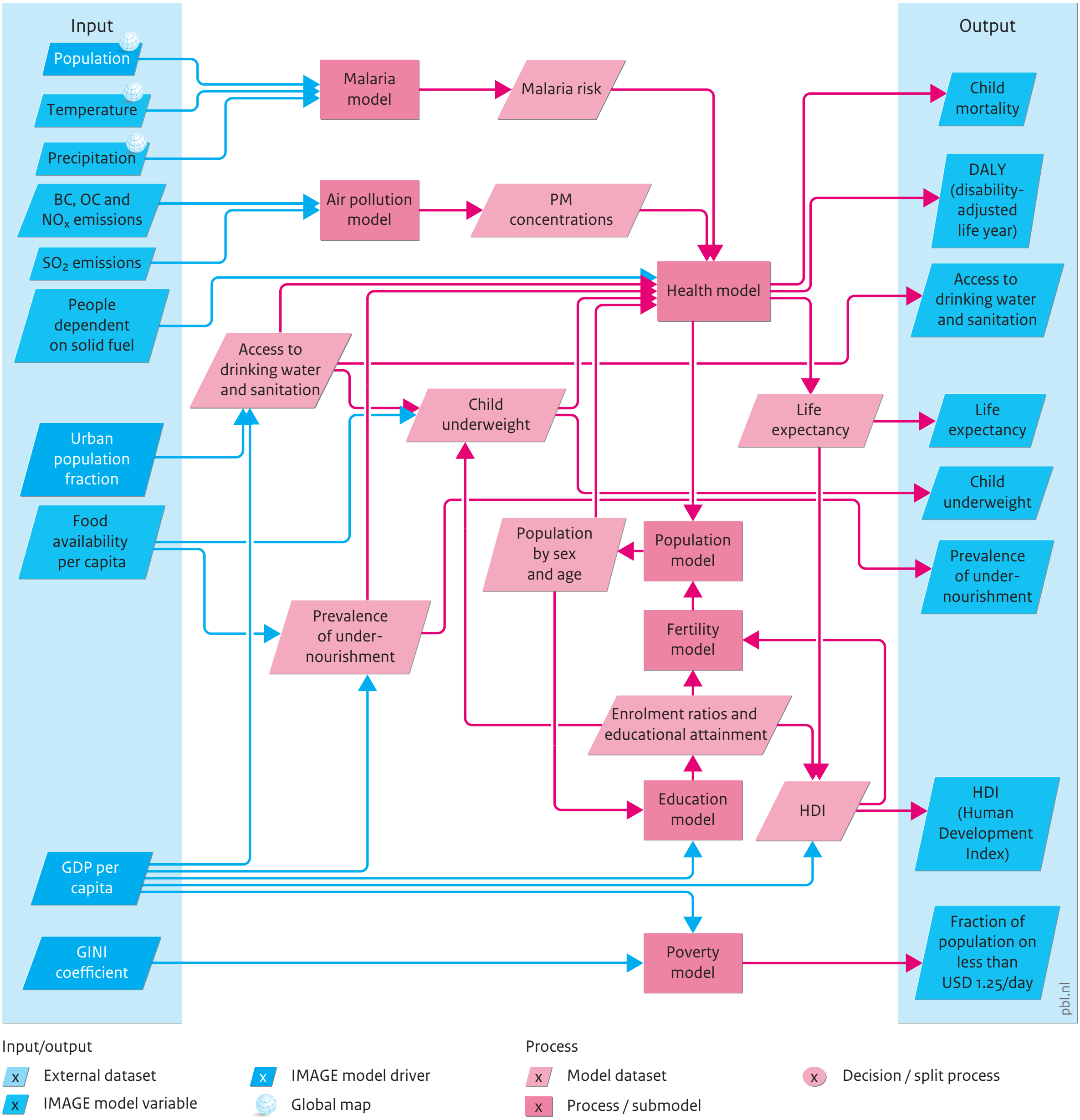
1. Introduction

The quantity and quality of accessible environmental resources determine the viability of livelihoods. Unequal access to, and diminished quality of resources have a significant effect on livelihoods and on human health, particularly in developing countries. Increasing world population accompanied by rising demand for food, water and energy will put even more pressure on scarce natural resources, such as fertile land, potable water and forest resources. The pressure will be even greater in areas where natural resources are not well managed and or were degraded as a result of global environmental change.

On all scales from global UN processes to local initiatives, decision makers are concerned with improving the standard of living and human development. The IMAGE framework provides valuable insights into key environmental factors that affect human development, and how these impacts may be reduced by improving the natural environment.

In the IMAGE framework, the Global Integrated Sustainability Model (GISMO) quantifies changes in human development, including access to sanitation, food and energy, and the impact of economic, social and environmental changes (Hilderink and Lucas, 2008). The model also includes the Human Development Index (HDI), population health measures (e.g. child mortality and life expectancy), and many indicators for the Millennium Development Goals (MDGs).

Figure 7.7.1
GISMO model to assess human development in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 7.7.1).

Those parts of GISMO directly linked to other parts of IMAGE, are climate-related health risks, health problems related to urban and indoor air pollution, and the effects of malnutrition.

2. Model description

GISMO assesses the impacts of global environmental change on human development through the impacts on human health either directly, for example the impact of climate change on malaria, or indirectly through, for instance, the impact of climate change on food availability. In addition to environmental factors, human health is also driven by socioeconomic factors, including income and education levels.

To take account of the interrelationships between the various factors, GISMO consists of three modules that address human health, poverty and education (Figure 7.7.1). The modules are linked through a cohort component population model that includes endogenous fertility and mortality (for details see Hilderink, 2000). Fertility levels are modelled using a convergence level that is determined by female educational levels, and speed of convergence determined by the human development index, and mortality rates by the health module. Future trends in migration, including urbanisation, are exogenous inputs to the model (for details see Hilderink, 2000).

The Human development index (HDI), which was introduced in the UNDP Human Development Report 1990 to rank development achievements, is a composite index of life expectancy, education, and income indices (UNDP, 1990; UNDP, 2010). While the underlying indicators have been refined several times, the three elements have remained the same. The index links to the three GISMO model components.

GISMO health module
This module describes the causal chains between health-risk factors and health outcomes (morbidity and mortality) and takes into account the effect of health services. The mortality rate is modelled by a risk-factor-attributable component and a non-attributable component. Historically, the non-attributable component represents mortality not covered by the risk factors included. For future projections, this component is assumed to reduce by the average regional historical rates of reduction.

The risk-factor-attributable component is based on a multi-state approach that distinguishes exposure, disease and death (WHO, 2002; Cairncross and Valdmanis, 2006). This implies that incidence and case fatality rates (ratio of the number of deaths from a specific disease to the number of diagnosed cases) are taken into account for various health-risk factors. Case fatality rates are modified by the level of health services. This method is used for malaria, diarrhoea and pneumonia. The method for projecting mortality due to other causes (non-communicable chronic diseases, other communicable diseases and injuries) follows the global burden of disease (GBD) approach. This method uses a parsimonious regression technique to relate mortality rates with GDP, smoking behaviour and human capital, in ten major disease clusters (Mathers and Loncar, 2006). This method is also used in determining death related to urban air pollution.

Table 7.7.2
Cause of death and environmental risk factors

Cause of death	Risk factors
Malaria	Climate suitable for malaria vectors
Protein deficiency	Prevalence of underweight
Diarrhoea	Lack of safe drinking water and basic sanitation
Pneumonia, Chronic obstructive pulmonary disease (COPD), Lung cancer	Use of solid fuels (traditional biomass or coal) for cooking and heating
Lung cancer, Cardiopulmonary diseases, Acute respiratory infections (ARI)	Exposure to PM_{10} and $PM_{2.5}$, related to NO_x, SO_2 and black carbon emissions

The GISMO health module takes into account mortality due to a range of diseases and conditions. These include malaria; communicable and infectious diseases associated with undernourishment, limited access to safe drinking water and basic sanitation and poor indoor air quality; diseases caused by poor outdoor air quality; HIV-AIDS; and chronic diseases including high blood pressure and obesity. Only the first three causes of mortality are considered because these are linked to environmental factors. The mortality rate due to a specific disease is a multiplication of the incidence rate (fraction of the population with the specific disease) and the case fatality rate (the fraction of people who die from a specific disease), distinguishing for the two sexes and five-year age cohorts. These mortality rates can then be used to calculated age-specific life expectancy (for details see Hilderink, 2000).

Malaria risk. Incidence rates of *malaria* are determined by the areas suitable for the malaria mosquito, based on monthly temperature and precipitation, see Section 6.5: Atmospheric composition and climate (Craig et al., 1999). Incidence rates are decreased by the level of insecticide treated bed nets and indoor residual spraying, modelled separately as potential policy options. The case fatality rate of malaria is increased by level of underweight people and decreased by case management (treatment).

Access to food, water and energy. GISMO relates incidence and case fatality rates for specific diseases to access to food, water and energy (Table 7.7.2). Access is defined by per capita food availability, access to safe drinking water and improved sanitation, and access to modern energy sources for cooking and heating. The future per capita food availability (Kcal/cap/day) is obtained from IMAGE (Section 4.2: Agriculture and land use). The levels of access to safe drinking water and improved sanitation are modelled separately by applying linear regression. The explanatory variables include GDP per capita, urbanisation rate and population density. Improvements in water supply are assumed to be implemented ahead of sanitation. Access to water supply and sanitation follows a pathway from no sustainable access to safe drinking water and basic sanitation, to improved water supply only, improved water supply and sanitation, household connection for water supply, to household connection to water supply and sanitation. Three levels of access to modern energy sources for cooking and heating are distinguished: traditional biomass and coal on traditional stoves; traditional biomass and coal on improved stoves; and use of modern energy carriers (electricity, natural gas, LPG, kerosene, modern biofuels and decentralised renewable sources). Trends in access to modern energy sources are taken from the TIMER energy demand module (Section 4.1.1).

Underweight children and prevalence of undernourishment. For children under the age of five, undernourishment is expressed as underweight (measured as weight-for-age), and prevalence of undernourishment is used for the rest of the population. The direct effect of undernourishment is protein deficiency, which for mortality rates of the under fives is scaled to their underweight status and for other age groups to the level of undernourishment. Undernourishment indirectly increases the incidence of diarrhoea and pneumonia, and the case fatality of malaria, diarrhoea and pneumonia. These indirect effects are only modelled for children under the age of five. Underweight children as the result of chronic undernourishment is modelled as a function of improvements in average food intake, ratio of female to male life expectancy at birth, female enrolment in secondary education and access to clean drinking water (Smith and Haddad, 2000). Based on a normal distribution, the total number of underweight children is divided into three groups of mildly, moderately and severely underweight (De Onis and Blossner, 2003).

The prevalence of undernourishment is calculated from per-capita food availability and minimum energy requirements (FAO, 2003). The calculations use a lognormal distribution function determined by mean food consumption and a coefficient of variation, which decreases over time as a function of per capita GDP. The minimum requirement of dietary energy is derived by aggregating region-specific, sex-age energy requirements weighted by the proportion of each sex and age group in the total population, including a pregnancy allowance.

Incidence rates of pneumonia, chronic obstructive pulmonary disease (COPD) and lung cancer are increased by indoor air pollution caused by cooking and heating with traditional biomass and coal. Simultaneously, incidence rates and case fatality rates are increased by child underweight levels. Incidence rates of diarrhoea depend on levels of access to drinking water and sanitation, levels of underweight children, and also on climate change. Case fatality rates are increased by underweight levels and decreased by the level of oral rehydration therapy.

Mortality associated with urban air pollution. Mortality rates of lung cancer, cardio-pulmonary diseases and acute respiratory infections due to urban air pollution (PM_{10} and $PM_{2.5}$ concentration levels) are derived using the GBD method (Mathers and Loncar, 2006). Based on emissions of NO_x, SO_2 and black carbon (Section 5.2, Emissions), PM_{10} concentration levels are determined using the Global Urban Air quality Model (GUAM). This model originates from the GMAPS model (Pandey et al., 2006), which determines PM_{10} concentration levels by economic activity, population, urbanisation and meteorological factors. $PM_{2.5}$ concentrations are obtained using a region-specific PM_{10}–$PM_{2.5}$ ratio. Based on these levels and the exposed population, mortality attributable to causes of death is derived using relative risks obtained from epidemiology studies (Dockery et al., 1993; Pope et al., 1995).

GISMO poverty module

The poverty line is commonly defined as the level at which consumption or income levels fall below that required to meet basic needs. In the model, the poverty head count (people living below the poverty line) is conducted by applying a log-normal distribution using per-capita income and a GINI coefficient to describe poverty distribution over a population. The poverty module can assess the number of people living below a poverty line, including the international poverty line defined as USD 1.25 per day, at 2005 PPP, by the World Bank (Ravallion et al., 2008).

GISMO education module

The education module assesses future developments in school enrolment and educational attainment, including literacy rates at three levels of education: primary, secondary and tertiary. The model tracks the proportion of the highest level of education completed and the average number of years of schooling per cohort.
The enrolment ratios per educational level are determined using cross-sectional relationships with per-capita GDP (PPP). The age at which a certain educational level is attained is assumed to be identical in all regions. Literacy rates are determined by the proportion of the population over the age of 15 who have completed at least primary education. Furthermore, to take account of autonomous increases in literacy levels, literacy levels of the population between the age of 15 and 65 is increased by 0.3%, annually.

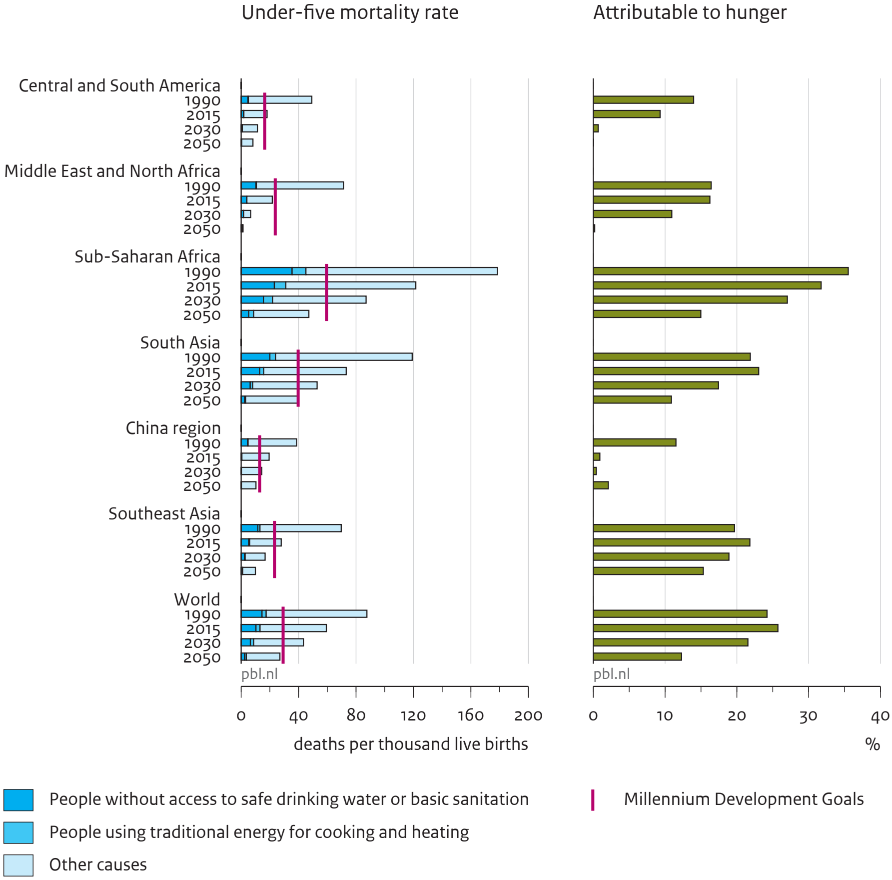
3. Policy issues

Baseline developments

The GISMO model has been used to evaluate various baseline scenarios, including that for the Rio+20 study (PBL, 2012). In most of these scenarios, access to food, improved drinking water, basic sanitation and modern energy sources all increase significantly up to 2050. Yet, even under large increases in access levels, a significant proportion of the population will still be without adequate services, mainly in Sub-Saharan Africa and South Asia. By 2050, around 300 million people will live below a minimum level

Figure 7.7.2

Child mortality under a baseline scenario, per cause, per region



Source: PBL 2012

Under a baseline scenario, the global under-five mortality rates will only reach the level of the Millenium Development goals by 2050.

of food energy consumption, 250 million without sustainable access to safe drinking water, 1.4 billion without basic sanitation and 1.9 billion without access to modern energy sources for cooking and heating. Global child mortality is projected to reduce significantly, from 67 deaths per 1000 children born in 2010 to fewer than 45 by 2030 and 28 by 2050, with large improvements in all world regions (Figure 7.7.2). To comply with the MDG on child mortality (MDG4), the under-five mortality rate should be reduced by two-thirds, between 1990 and 2015. Without new policies, this target will not be achieved, mainly due to persistent high levels of child mortality in Sub-Saharan Africa and South Asia (see also PBL, 2009).

Policy interventions

Policy interventions to decrease human health loss and child mortality rates can be classified as (i) prevention through eliminating or reducing health risks; and (ii) treatment through investing in health systems to reduce deaths from a specific disease or due to a specific health hazard.

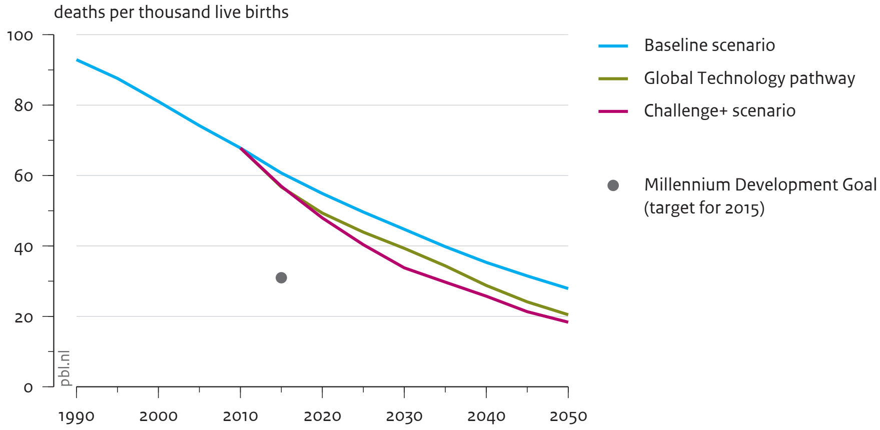
Prevention in order to eliminate or reduce health risks is generally implemented by:

- increasing access levels by lowering prices and investing in infrastructure;
- improving the quality of access through, for example, household connections to the drinking-water supply and use of LPG or kerosene instead of using improved biomass stoves;
- improving behaviour through women's education, hygiene measures and better house ventilation;
- mitigating environmental changes, such as climate change, biodiversity loss and water stress.

GISMO addresses access to drinking water and sanitation, quality of access and behavioural issues. Access to food and energy and mitigating environmental changes is addressed in other components of the IMAGE framework. GISMO can be used to explore how sustainability goals related to human well-being, such as reducing under-five mortality, can be achieved (Figure 7.7.3). In a recent study, two scenarios were developed (PBL 2012). In the first scenario ('global technology') full access to food, water and energy is induced. In this scenario, all people will have access to modern energy sources for cooking and heating by 2030 by subsidising modern energy sources and distributing improved biomass stoves. Furthermore, all people will have access to safe drinking water and improved sanitation by 2050 (exogenous assumption). Finally, hunger will be eradicated by 2050 by increasing global food production, specifically targeting staples such as wheat, rice and other cereals. The second scenario ('challenge + ') adds quality of access with respect to water and energy and assumes full enrolment of girls in secondary education by 2030.

As a result of the policy interventions described above, global child mortality rates are projected to decline by 12% by 2030, and by more than 26% by 2050, in the 'global technology' scenario compared to the baseline scenario (Figure 7.7.3). The additional policies in the second scenario are stylised in the sense that they are not calculated using the full modelling framework and, therefore, do not take into account all socioeconomic and environmental constraints. Under this scenario, child mortality delines by almost 25% by 2030 and by 34% by 2050, compared to the baseline scenario. However, in neither of the two scenarios MDG4 is achieved.

Figure 7.7.3
Global under-five child mortality rate under baseline and sustainability scenarios



Source: PBL 2012

Compared to the baseline, the sustainability scenarios 'Global Technology' and 'Challenge+' (PBL, 2012) will reduce child mortality, but the MDG target set for 2015 would still only be met after 2030.

4. Data, uncertainties and limitations

Data
Most data used in GISMO originate from specific UN institutions or the World Bank (Table 7.7.3).

Table 7.7.3
Data sources of the GISMO model

Data	Source.
Per-capita food intake and coefficient of variation	(FAO, 2012a)
Region-specific sex-age energy requirements	(FAO, 2001b)
Access to safe drinking water and basic sanitation	(WHO/UNICEF, 2012)
People using solid fuels and improved biomass stoves	(Hutton et al., 2006)
Health risks and disease burden	(WHO, 2009)
Health and education expenditures	(World Bank, 2009)
Poverty data	(Chen and Ravallion, 2008)
GINI coefficients	(Ackah et al., 2009)
Enrolment ratios per educational level and	(World Bank, 2009)
Educational attainment level	(Lutz et al., 2007)

Uncertainties

The broad range of issues addressed leads to a range of uncertainties. Only the data uncertainties related to access to food, water and energy and the related health risks are considered.

Per-capita food intake is based on FAOSTAT data, applied as averages per region, in the first year, and extended into the future by using food consumption data from the agro-economic model MAGNET (Section 4.2.1). The trends in per-capita food availability use income elasticities for broad groups of crops and animal products, but these trends are not necessarily linked to physical limitations on consumption levels. For water and energy, aggregations of different technologies to broad groups mask the underlying heterogeneity, and thus lead to uncertainties in model behaviour. Improved access to water supply and sanitation encompasses a broad range of forms of connection, each of which is assumed to carry the same potential health risk. The same is the case for access to modern energy sources for cooking and heating that encompass a broad range of traditional fuel and fuel-stove combinations. Health impacts are based on exposure-response relationships, and these are assumed to be the same worldwide and to remain constant over time. Many parameters are based on cross-sectional relationships with per-capita GDP (PPP), making the outcomes heavily dependent on this parameter.

Limitations

The model also has several limitations, and specifically limited representation of the heterogeneous characteristics within populations. In most cases, a population average combined with a stylised distribution function is applied. This may not fully represent the distributional aspects, as in reality many of these issues may be concentrated in particular populations, and, more importantly, these distribution functions do not change in the model over time, while they probably do in reality.

Furthermore, although health service efficacy and school enrolment ratios are driven in the model by investments in health and education services, these investments are not restricted by a limit on total investments. Similarly, the investments in drinking water and sanitation are not made explicit in the model but are derived from achieved coverage. Thus, instead of analysing the effect of specific investments in health outcomes, analysis can only be done by using pre-determined what-if scenarios.

5. Key Publications

Hilderink, H.B.M. and Lucas P.L. (eds.) (2008). Towards a global integrated sustainability model: GISMO 1.0 status report. A. ten Hove, M.T.J. Kok, M.G. de Vos, P.H.M. Janssen, J.R. Meijer, A. Faber, A. Ignaciuk, A.C. Petersen and H.J.M. de Vries, PBL Netherlands Environmental Assessment Agency, The Hague.
PBL (2009). Beyond 2015: Long-term development and the Millennium Development Goals, H.B.M. Hilderink, P.L. Lucas and M. Kok (eds.). PBL Netherlands Environmental Assessment Agency, Bilthoven/The Hague, www.pbl.nl/en/publications/2009/Beyond-2015_-Long-term-development-and-the-Millennium-Development-Goals.
PBL (2010). Rethinking global biodiversity strategies, B. ten Brink, S. Van der Esch, T. Kram, M. Van Oorschot, R. Alkemade, R. Ahrens, M. Bakkenes, J. Bakkes, M. Van den Berg, V. Christensen, J. Janse, M. Jeuken, P. Lucas, T. Manders, H. Van Meijl, E. Stehfest, A. Tabeau, D. Van Vuuren and H. Wilting. PBL Netherlands Environmental Assessment Agency Bilthoven/The Hague, www.pbl.nl/en/publications/2010/Rethinking_Global_Biodiversity_Strategies

6. Input/Output Table

Table 7.7.1
Input in and output from the human development model GISMO

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
GINI coefficient	Measure of income disparity in a population. If all have the same income, GINI equals 1. The lower the GINI, the wider the gap between the lowest and highest income groups.	3
Urban population fraction	Urban/rural split of population.	3
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	3
Population - grid	Number of people per gridcell (using downscaling).	3
Precipitation - grid	Monthly total precipitation.	6.5
Food availability per capita	Food availability per capita.	4.2.1
Temperature - grid	Monthly average temperature.	6.5
People dependent on solid fuel	Proportion of population using traditional biomass and coal for cooking and heating.	4.1.1
BC, OC and NOx emissions	Emissions of BC, OC, SO2 and NOx per year.	5.2
SO2 emissions	SO2 emissions, per source (e.g. fossil fuel burning, deforestation).	5.2
Output	**Description**	**Use (section)**
Child underweight	Prevalence of undernourishment in children.	Final output
Child mortality	he probability per 1,000 that a new-born baby will die before reaching the age five, if subject to average age-specific mortality rates.	Final output
Prevalence of undernourishment	Proportion of the population with insufficient food intake to meet dietary energy requirements.	Final output
Life expectancy	Average life expectancy of a person born in a given year.	Final output
People living on less then USD 1.25 per day	People living on less than $1.25 a day	Final output
DALYs (disability-adjusted life years)	The disability-adjusted life year (DALY) is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability and early death.	Final output
Access to drinking water and sanitation	Percentage of the population with sustainable access to safe drinking water and basic sanitation.	Final output
HDI (human development index)	HDI: Development level of a country based on income, education and life expectancy.	Final output

POLICY RESPONSES

POLICY RESPONSES

8 Policy responses

The IMAGE model can be used to analyse a range of policy measures. The most important policy domains covered by IMAGE are climate policy, energy policy, and land and biodiversity policies. For these key domains, Sections 8.1 to 8.3 discuss the type of policies and measures that can be analysed and how policy responses impact different parts of the IMAGE model. Clearly, the IMAGE framework can also be used to analyse other policy domains, such as human development, nutrients balances or water scarcity. For these topics, information on policy responses can be found in the relevant sections. Finally, it should be noted that for climate policy the IMAGE framework uses a separate model called FAIR (Section 8.1), while for Energy policy (Section 8.2) and for Land and biodiversity policies (Section 8.3), the relevant policy interventions are implemented in various IMAGE components.

8.1 Climate policy

Michel den Elzen, Andries Hof, Maarten van den Berg, Mark Roelfsema

Key policy issues

- What global greenhouse gas emissions pathways would meet the 2 °C climate target?
- What is the effect of effort-sharing approaches on regional and national emission reduction targets and on the cost of climate policies?
- How do current national reduction proposals (pledges) contribute to achieving the 2 °C climate target?
- What are the trade-offs between mitigation costs, adaptation costs, and climate change damage?

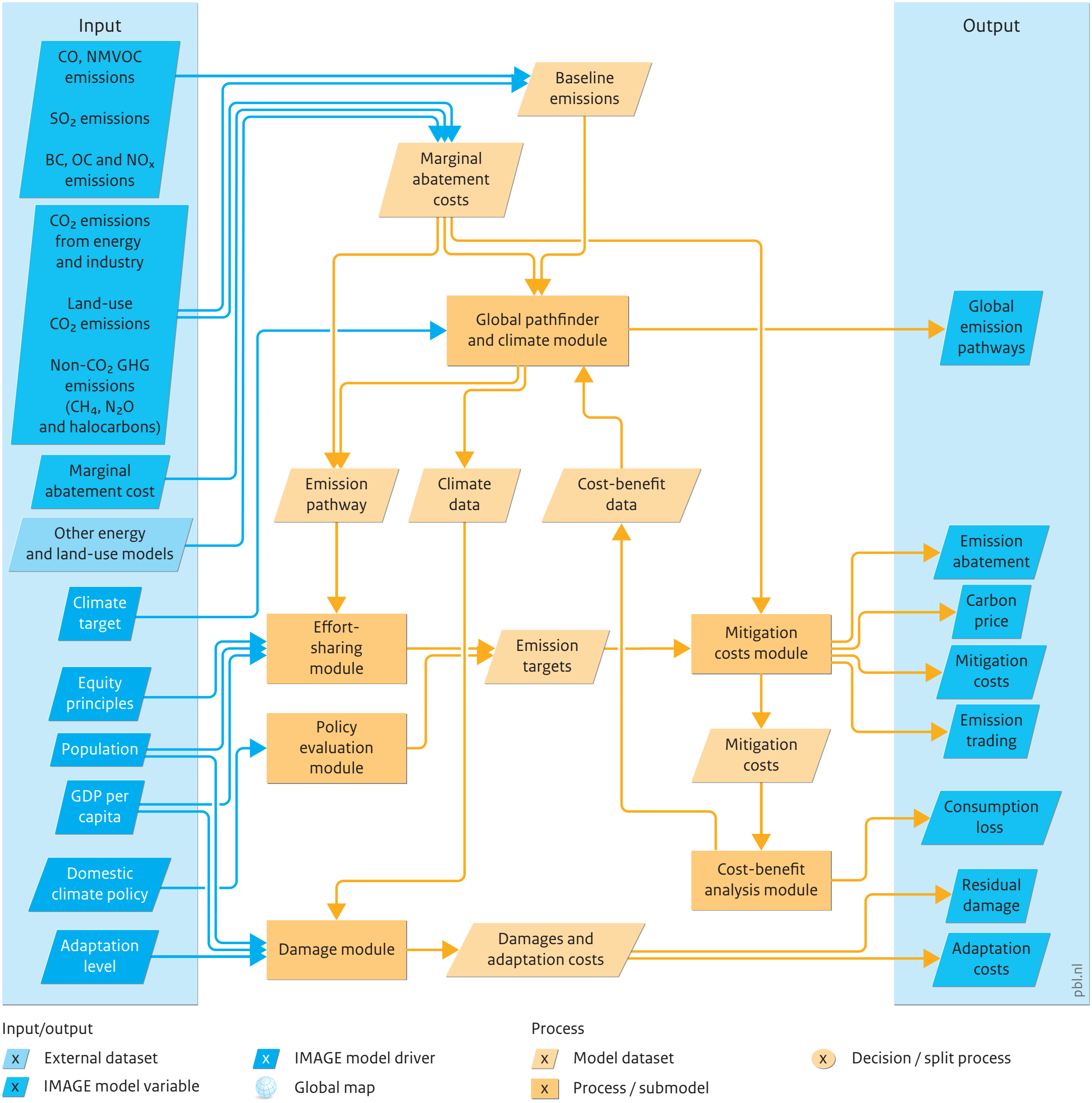
1. Introduction

The United Nations climate negotiations called for urgent action to limit global warming to 2 °C compared to pre-industrial levels. To achieve this goal, countries have proposed short- and long-term reduction targets in the UNFCCC climate negotiating process and in domestic policies. To support climate policymakers, the IMAGE model is used in conjunction with the climate policy model FAIR. FAIR is a decision support tool to analyse the costs, benefits, and climate effects of mitigation regimes, emission reduction commitments, and climate policies.

FAIR can work in stand-alone mode using exogenous data, but in recent applications it interacts with several IMAGE components. For instance, mitigation cost curves for the energy sector are derived from the Energy Supply and Demand model TIMER (Section 4.1) and land-use mitigation options from Agriculture and Land Use (Section 4.2). Data from FAIR on marginal abatement costs and reduction efforts per sector and greenhouse gases are used as input for IMAGE to evaluate the impacts under different assumptions for climate mitigation.

FAIR in combination with IMAGE can analyse the interaction between long-term climate targets and short-term regional emission targets. Regional targets are based on effort-sharing approaches and/or national emission reduction proposals, taking into account decisions on accounting rules as agreed under the UNFCCC. The central purposes of the model are the calculation of mitigation costs and trade in emission allowances, and the net mitigation costs of a region to achieve its mitigation target. FAIR enables evaluation of proposed effort-sharing regimes, including differentiated timing and participation of a limited number of parties to the climate convention. Furthermore, FAIR analyses the trade-offs between costs and benefits of mitigation and adaptation policy.

Figure 8.1.1
FAIR, the climate policy model in IMAGE 3.0



Source: PBL 2014

More detail on inputs and outputs, and how they link to other IMAGE components is presented at the end of this section (Table 8.1.1).

2. Model description

FAIR consists of six linked modules as presented in Figure 8.1.1 and described briefly below.

The **Global pathfinder and climate** module. The pathfinder module FAIR-SiMCaP calculates global emission pathways that are consistent with a long-term climate target (Den Elzen et al., 2007; Van Vliet et al., 2009; Van Vuuren et al., 2011b). Inputs are climate targets defined in terms of concentration levels, radiative forcing, temperature, and cumulative emissions. In addition, intermediate restrictions on overshoot levels or intermediate emission targets representing climate policy progress can be included. The model combines the FAIR mitigation costs model and a module that minimises cumulative discounted mitigation costs by varying the timing of emission reductions. For climate calculations, FAIR-SiMCaP uses the MAGICC 6 model, with parameter settings calibrated to reproduce the medium response in terms of time scale and amplitude of 19 IPCC AR4 General Circulation Models (Meinshausen et al., 2011b).

The **Policy evaluation** module calculates emission levels resulting from the pledges and mitigation actions submitted by developed and developing countries as part of the 2010 UNFCCC Cancún Agreements (Den Elzen et al., 2013; Hof et al., 2013). Next, this module analyses the impact of planned and/or implemented domestic mitigation policies, such as carbon taxes, feed-in tariffs and renewable targets, on national emissions by 2020 to determine whether countries are on track with their reduction pledges (Roelfsema et al., 2014). The module is used in conjunction with a wide range of evaluation tools developed in cooperation with IIASA, JRC and ECOFYS, such as tools for analysing policy options for land-use credits and surplus emissions.

The **Effort sharing** module calculates emission targets for regions and countries, resulting from different emission allocation or effort-sharing schemes (Den Elzen et al., 2012a; Hof et al., 2012). Such schemes start either at the global allowed emission level, after which the effort-sharing approach allocates emission allowances across regions, or at the required global reduction level, after which various effort-sharing approaches allocate regional emission reduction targets. Both approaches use information from the Global Pathfinder and Climate module on the required global emission level or emission reductions. As an alternative, emission allowances can be allocated to regions without a predefined global reduction target, based on different effort-sharing approaches. The model includes effort-sharing approaches such as Contraction & Convergence, common-but-differentiated convergence, and a multi-stage approach.

The **Mitigation costs** module is used for calculating the regional mitigation costs of achieving the targets calculated in the Policy Evaluation and/or the Effort Sharing modules, and to determine the buyers and sellers on the international emissions trading market (Den Elzen et al., 2008; Den Elzen et al., 2011a). Inputs to the model are regional gas- and source-specific Marginal Abatement Cost (MAC) curves that reflect the additional costs of abating one extra tonne of CO_2 equivalent emissions. The MAC curves describe the potential and costs of the abatement options considered. The model uses aggregated regional permit demand and supply curves derived from the MAC curves to calculate the equilibrium permit price on the international trading market, its buyers and sellers, and the resulting domestic and external abatement per region. The design of the emissions trading market can include: constraints on imports and exports of emission permits; non-competitive behaviour; transaction costs associated with the use of emission trading; a less than fully efficient supply of viable CDM projects with respect to their operational availability; and the banking of surplus emission allowances.

The **Damage** and **Cost-Benefit Analysis** modules calculate the consumption loss resulting from climate change damage, and compare these with the consumption losses of adaptation and mitigation costs (Hof et al., 2008; 2009; 2010). Estimates of adaptation costs and residual damage (defined as the damage that remains after adaptation) are based on the AD-RICE model (De Bruin et al., 2009), which are based on total damage projections made by the RICE model. Calibration of the regional adaptation cost functions is based on an assessment of each impact category described in the RICE model, using relevant studies and with expert judgement where necessary. The optimal level of adaptation can be calculated by the model, but may also be set to a non-optimal level by the user.

Consumption losses due to mitigation, adaptation and climate change damage are estimated based on a simple Cobb-Douglas economic growth model. Each region is calibrated separately to the exogenous GDP path. Damages, adaptation and abatement costs are subtracted from investment or consumption to determine either the direct replacement effect on consumption, or the indirect effect from replacing investments.

3. Policy issues

Baseline developments

FAIR can be used to analyse baseline developments, such as expected climate change damage. However, more often baseline developments are explored using the larger IMAGE framework, and the FAIR model receives this information as input for policy analysis.

Policy interventions

As part of the IMAGE framework, FAIR can be used to evaluate a range of policies and strategies, including:

- Long-term mitigation strategies such as emission reductions over time (Den Elzen et al., 2007; Den Elzen and Van Vuuren, 2007; Van Vliet et al., 2009; Van Vuuren et al., 2011b; 2012);

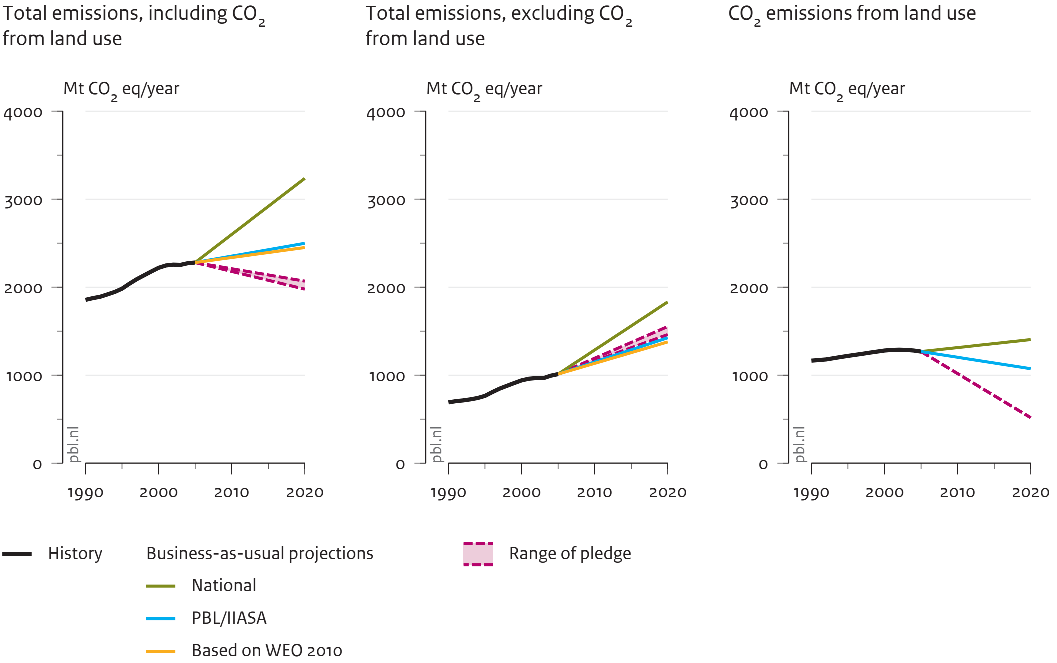
- Evaluation of current reduction proposals by countries and policy options for the next 10 to 20 years (European Commission, 2010; Den Elzen et al., 2011a; 2011b; 2012b; UNEP, 2012; Hof et al., 2013);
- Evaluation of domestic climate and energy policies for the next 10 to 20 years (Höhne et al., 2012; Roelfsema et al., 2013; 2014);
- Evaluation of burden sharing or effort sharing regimes (Den Elzen and Höhne, 2010; Den Elzen et al., 2012a; Hof et al., 2012);
- Analysis of regional abatement costs and emission trading (Den Elzen et al., 2008; Den Elzen et al., 2011a; Mendoza Beltrán et al., 2011);
- Evaluation of proposals for financing climate policies (Hof et al., 2009; 2011);
- Evaluation of trade-offs between mitigation costs, adaptation costs and the benefits of reduced climate damage (Hof et al., 2008; 2009; 2010).

The FAIR Policy Evaluation module has been used in determining emission reductions resulting from pledges made for 2020 (Den Elzen et al., 2012c). In 2011, Brazil presented a new, higher estimate for national business-as-usual (BAU) emissions, against which a 36 to 39% reduction pledge was made. The total pledge for all greenhouse gas emissions including emissions from deforestation was a reduction of 20 to 24% compared to the PBL/IIASA BAU emission projections. This reduction is substantially lower than pledged by Brazil from national BAU projections.

As shown in Figure 8.1.2, all reductions result from reduced emissions from deforestation (REDD). The contributions from REDD projects (about 560 MtCO_2) are expected to exceed or match the required total reduction in all greenhouse gas emissions of 470 and 570 Mt CO_2eq for the 36% and 39% reduction pledge scenarios.

The Global Pathfinder module was used to determine what the pledges for 2020 imply for global emission pathways consistent with meeting the 2 °C target (Van Vliet et al., 2012). The main findings were as follows (see also, Figure 8.1.3):
- The global 2020 emission level resulting from implementation of the Copenhagen Accord pledges exceeds those of least-cost pathways that achieve a 2 °C target;
- Slightly postponing mitigation action (potential Copenhagen scenario) compared to the least-cost scenario seems technically feasible but at higher cumulative discounted mitigation costs;
- For an even longer delay (the current Copenhagen scenario), the FAIR-SiMCaP model cannot fully compensate the higher emission level in the short term;
- A delay in emission reductions limits the flexibility in the portfolio of emission reduction options. Such delayed scenarios rely more on the use of bioenergy with carbon capture and storage (BECCS), an option with uncertain prospects for large-scale implementation.

Figure 8.1.2
Greenhouse gas emissions under baseline scenarios and pledges, for Brazil



Source: Den Elzen et al. 2013

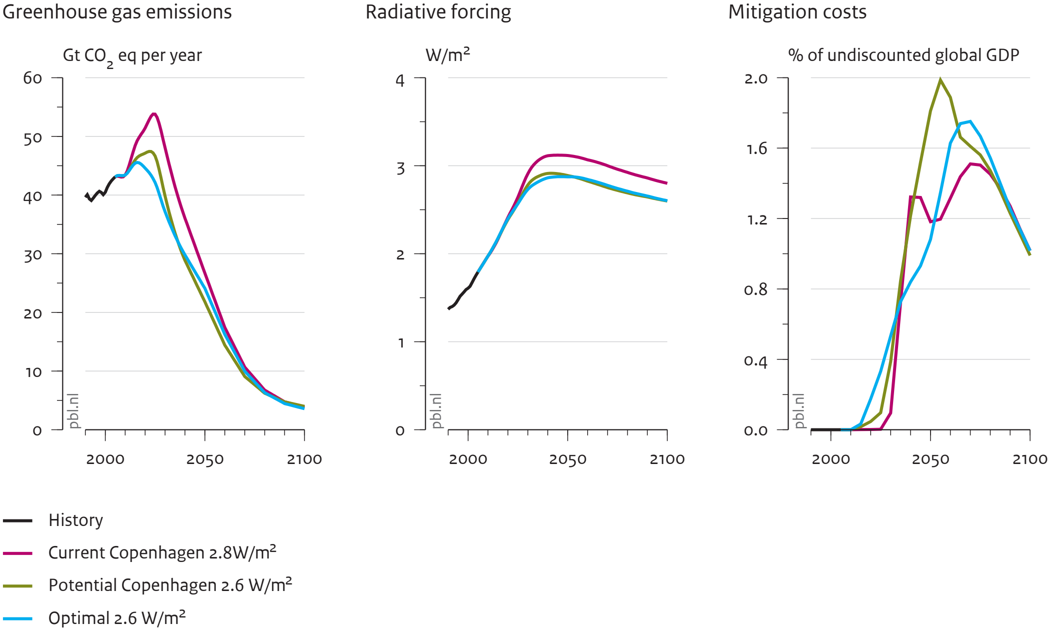
The national projection is from the National Decree No. 7390, and the WEO 2010 projection is from the World Energy Outlook (2010) of International Energy Agency.

4. Data, uncertainties and limitations

Data

Input for the modules consists of baseline scenarios on population, GDP and emissions, as calculated by the IMAGE modelling framework. Emissions are from all major sources and include all six Kyoto greenhouse gases. MAC curves describing mitigation potential and costs of greenhouse gas emission reductions are derived from the TIMER energy model and the IMAGE land-use model. The MAC curves take into account a wide range of options, including carbon plantations, carbon capture and storage (CCS), bio, wind and solar energy, and energy efficiency and technological improvements. In addition, FAIR can also use emission projections and MACs from other models, such as the POLES energy system model (Enerdata, 2010a) and IIASA land-use models (Kindermann et al., 2008), to assess the sensitivity of the outcomes to these inputs.

Figure 8.1.3
Greenhouse gas emissions, radiative forcing and costs under mitigation scenarios



Source: Van Vliet et al. 2012

Scenarios of optimal and delayed policy action (Copenhagen pledges) differ in terms of emissions, associated radiative forcing, and global mitigation costs.

Uncertainties

Each FAIR module has uncertainties. The main uncertainties in the cost modules are future business-as-usual emission trends (higher emission trends imply higher mitigation costs to achieve a certain target) and MAC curves (difficult to estimate the costs of reducing emissions far into the future). In the Global Pathfinder and Climate module, uncertainty in the climate sensitivity of the climate system to greenhouse gas concentration is an key source of uncertainty but can be covered by using a probabilistic version of the MAGICC climate model. Probably the largest source of uncertainty relates to climate change damage, as there are few studies on the economic damage of climate change on a global or regional scale.

Limitations

A key limitation of the Global Pathfinder and Climate module is that the costs of climate policy are not fed back to the rest of the economy. Furthermore, some abatement technologies especially in the land system are assumed to have no effects on other parameters, such as crop yields. Some land-based mitigation technologies such as afforestation, and agricultural carbon management, are included in FAIR, but are not represented explicitly in the terrestrial vegetation system of the IMAGE framework.

5. Key publications

Den Elzen MGJ, Lucas P and Van Vuuren DP. (2008). Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent concentrations. *Climatic Change* 90(3), pp. 243–268.

Den Elzen MGJ, Hof AF, Mendoza Beltrán A, Grassi G, Roelfsema M, Van Ruijven BJ, van Vliet J and Van Vuuren DP. (2011a). The Copenhagen Accord: Abatement costs and carbon prices resulting from the submissions. *Environmental Science & Policy* 14, pp. 28–39.

Hof AF, de Bruin KC, Dellink RB, Den Elzen MGJ and Van Vuuren DP. (2009). The effect of different mitigation strategies on international financing of adaptation. *Environmental Science and Policy* 12(7), pp. 832–843.

Van Vliet J, Den Elzen MGJ and Van Vuuren DP. (2009). Meeting radiative forcing targets under delayed participation. *Energy Economics* 31(suppl. 2), pp. 152–162.

6. Input/Output Table

Table 8.1.1
Input in and output from the climate policy model FAIR

Input	Description	Source (section/ other)
IMAGE model drivers and variables		
Population	Number of people per region.	3
GDP per capita	Gross Domestic Product per capita, measured as the market value of all goods and services produced in a region in a year, and is used in the IMAGE framework as a generic indicator of economic activity.	3
Climate target	Climate target, defined in terms of concentration levels, radiative forcing, temperature targets, or cumulative emissions.	3
Domestic climate policy	Planned and/or implemented national climate and energy policies, such as taxes, feed-in tariffs, renewable targets, efficiency standards, that affect projected emission reduction.	3
Equity principles	General concepts of distributive justice or fairness used in effort sharing approaches. Three key equity principles are: Responsibility (historical contribution to warming); capability (ability to pay for mitigation); and equality (equal emissions allowances per capita).	3

Adaptation level	Level of adaptation to climate change , defined as the share of climate change damage avoided by adaptation. This level is be calculated by the model to minimise adaptation costs and residual damage, or set by the user.	3
CO_2 emission from energy and industry	CO_2 emission from energy and industry.	5.2
Land-use CO_2 emissions - grid	Land-use CO_2 emissions from deforestation, wood harvest, agricultural harvest, bioenergy plantations and timber decay.	6.1
Non-CO_2 GHG emissions (CH_4, N_2O and Halocarbons)	Non-CO_2 GHG emissions (CH_4, N_2O, Halocarbons).	5.2
SO_2 emissions	SO_2 emissions, per source (e.g. fossil fuel burning, deforestation).	5.2
BC, OC and NOx emissions	Emissions of BC, OC, SO_2 and NO_x per year.	5.2
CO and NMVOC emissions	Emissions from CO and NMVOC.	5.2
Marginal abatement cost	Cost of an additional unit of pollution abated (CO_2eq). A marginal abatement cost curve (MAC curve) is a set of options available to an economy to reduce pollution, ranked from the lowest to highest additional costs.	4.1.3
External datasets		
Other energy and land-use models	Emission projections and marginal abatement costs curves based on external models, such as the IIASA land-use models or the POLES database.	IIASA database, Enerdata (2010a)
Output	**Description**	**Use (section)**
Carbon price	Carbon price on the international trading market (in USD in 2005 per tonne C-eq) calculated from aggregated regional permit demand and supply curves derived from marginal abatement costs.	4.1.2
Emission abatement	Reduction in emission factors as a function of Climate policy.	5.2
Global emission pathways	Global emission pathway consistent with a specific long-term climate target.	Final output
Mitigation costs	Net costs of measures to reduce greenhouse gas emissions.	Final output
Consumption loss	Loss of private consumption due to mitigation and adaptation costs and residual damage.	Final output
Adaptation costs	Costs for adaptation measures to reduce the vulnerability of natural and human systems to actual or expected climate change effects.	Final output
Residual damage	Climate change damage remaining after adaptation.	Final output
Emission trading	Emission credits traded between regions	Final output

8.2 Air pollution and energy policies

Detlef van Vuuren, Paul Lucas, Bas van Ruijven

Key policy issues:

- How do energy policies contribute to economic and social development, and how do they support or hamper a more sustainable future?
- How can the goals for affordable, clean and reliable energy be achieved taking into account possible synergies and trade-offs?

1. Introduction

Many countries have formulated explicit policies to address the role of the energy system in achieving their development ambitions. These policies are clustered under goals for affordable energy, clean energy, and reliable energy. The EU Energy Strategy, for instance, aims for a competitive, sustainable and secure energy system (EC, 2010). Similarly, the UN Secretary-General Advisory Group on Energy and Climate Change (AGECC) states as goal ensuring reliable, affordable, and sustainable access to modern energy services (AGECC, 2010).

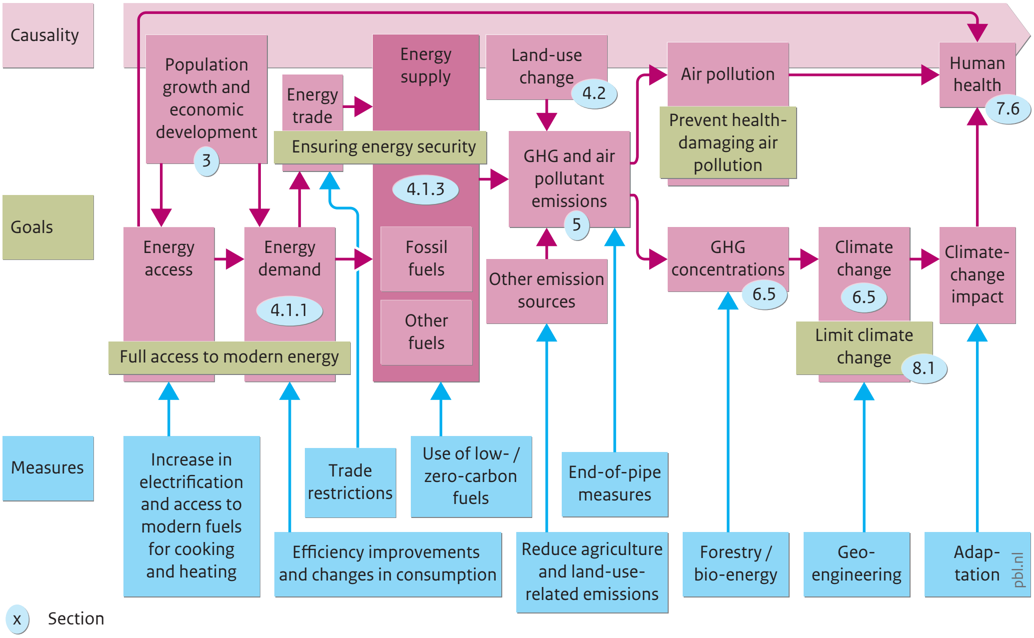
Other energy policies are also pursued. Energy exporting countries, for instance, aim to maximise returns on national fossil-fuel reserves. Many countries have formulated policies to support specific energy uses (e.g. irrigation) or user groups by offering energy at reduced costs, by subsidies or energy taxes exemptions , or by providing free grid connectivity. While inspired by other policy considerations, some of these measures rank as harmful subsidies from an environmental perspective.

The three energy goals represent trade-offs, but also opportunities for synergy, and model studies can help to identify and explore these. An important interaction is also with the climate policies discussed in Section 8.1.

Here, we focus on access to modern energy sources (affordable), air pollution reduction (clean) and energy security (reliable). Energy security concerns may limit use of foreign supplies, with possible implications for domestic energy prices and environmental impacts. Access to modern energy generates additional demands for fuel and electricity with benefits for economic development, but may also lead to more energy imports. Outside air pollution from burning fossil fuels may increase, but phasing out traditional

Figure 8.2.1

Linkages between goals and measures for energy access, energy security, climate change and air pollution



Source: PBL 2012

Linkages between components of the IMAGE system, energy policy objectives and possible policy measures.

bioenergy will substantially reduce indoor air pollution, resulting in net health improvements. Currently, in some regions and cities burning fossil fuels and biomass contributes to severe and increasing levels of air pollution and associated health impacts, see also Section 8.3.

2. Model description

Most processes relevant for energy policy goals are directly related to the IMAGE energy model (Section 4.1). The relationship of these processes to the goals formulated for energy systems is presented in Figure 8.2.1, which also provides examples of measures that can be taken in the system, and can be captured to some degree in the IMAGE system (see also Table 8.2.1).

3. Policy issues

The energy system is described in Section 4.1, and emissions in Section 5.2. As indicated in Figure 8.2.1, parts of the energy system are closely linked and thus achieving a specific policy goal has consequences for other goals. For instance, climate policies can lead to less use of fossil fuel, and thus also reduction in air pollution. How these goals are included in IMAGE is described briefly below.

Table 8.2.1
Policy interventions for energy policy goals in IMAGE 3.0

Policy intervention	Description and effect	Affected sections
Apply emission and energy intensity standards	Apply emission intensity standards for e.g. cars (gCO_2/km), power plants (gCO_2/kWh) or appliances (kWh/hour).	5.2
Capacity targets	It is possible to prescribe the shares of renewables, CCS technology, nuclear power and other forms of generation capacity. This measure influences the amount of capacity installed of the technology chosen.	4.1.2*, 5.2
Carbon tax	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives and energy efficiency more attractive.	4.1.1*,4.1.2, 4.1.3, 5.2,7.7, 8.1*
Change market shares of fuel types	Exogenously set the market shares of certain fuel types. This can be done to explore the broader implications of increasing the use of, for instance, biofuels, and reflects the impact of fuel targets.	4.1.1*,4.1.2, 4.1.3, 5.2,
Change the use of electricity and hydrogen	It is possible to promote the use of electricity and hydrogen at the end-use level.	4.1.1, 4.1.2*, 5.2,
Excluding certain technologies	Certain energy technology options can be excluded in the model for environmental, societal, and/or security reasons. (Kruyt et al., 2009).	4.1.2*, 5.2
Implementation of biofuel targets	Policies to enhance the use of biofuels, especially in the transport sector. In the Agricultural economy and forestry component , the policy is implemented as a budget-neutral policy from government perspective.	4.1.3, 4.2.1*, 4.2.3, 5.2, 7.2,
Implementation of sustainability criteria in bio-energy production	Sustainability criteria that could become binding for dedicated bio-energy production, such as the restrictive use of water-scarce or degraded areas.	4.1.3*, 5.2, 7.2
Improving energy efficiency	Exogenously set improvement in efficiency, . for example, in transport, heavy industry and households submodels.	4.1.1*, 4.1.2, 4.1.3, 5.2,

Production targets for energy technologies	Production targets for energy technologies can be set to force technologies through a learning curve.	4.1.2, 4.1.3
Provision on improved stoves for traditional bio-energy	Increases the efficiency of bio-energy use.	4.1.1*, 7.7
Restrictions on fuel trade	As part of energy security policies, fuel trade between different regions can be blocked.	4.1.2, 4.1.3*
Subsidies on modern energy	Reduces the costs of modern energy to reduce traditional energy use (can be targeted to low income groups).	4.1.1*, 7.7

* *Policy intervention is implemented in this module. A detailed list of all policy interventions that can be studied with IMAGE 3.0 is presented at www.pbl.nl/image*

Energy security: Baseline developments

While the concept of energy security is widely used, there is no consensus on its interpretation. Some focus on one aspect of energy security, such as resource estimates, reserve-to-production ratios, diversity indices and import dependence, while others attempt to capture several elements in a single aggregated index.

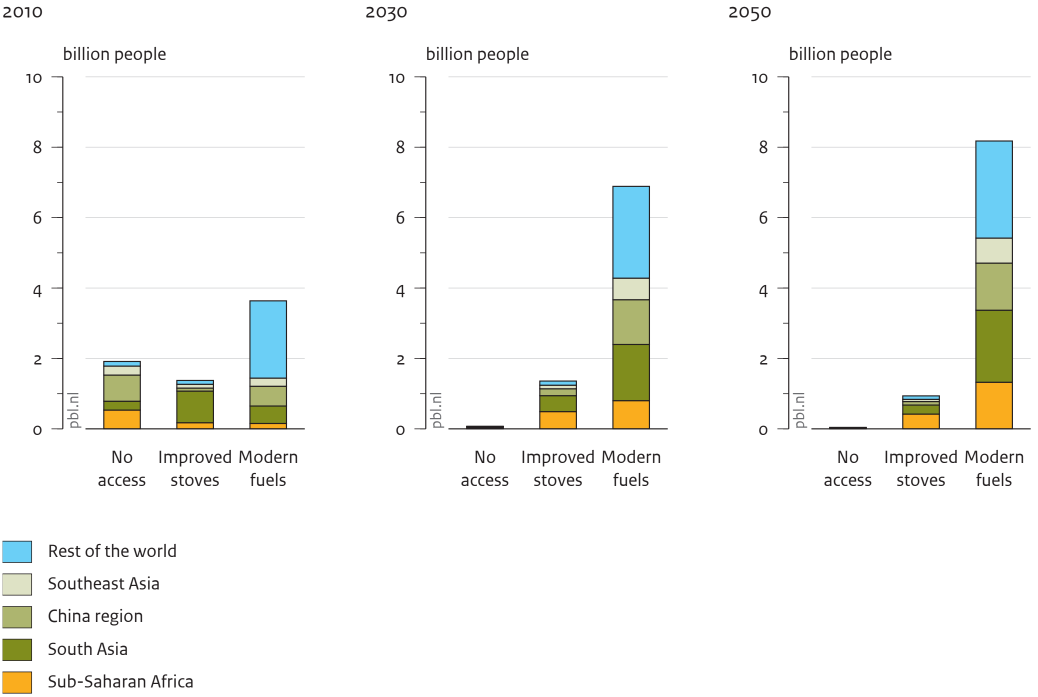
On the basis of IMAGE results, a wide set of indicators can be calculated to make a broad assessment of changes (Kruyt et al., 2009). IMAGE results show that in baseline scenarios without additional policy, depletion of known fossil resources accelerates as a result of increasing global demand. Oil production is projected to become increasingly concentrated in fewer producing countries in the 2010–2030 period. After 2030, the already existing trend towards unconventional oil (and gas) production will start to dominate and the market will diversify again. Under commonly used assumptions on resource assumptions, depletion dynamics for natural gas and certainly for coal play a small role in IMAGE results.

Energy security: Policy interventions

IMAGE is used to explore policies to improve energy security, by imposing import restrictions, modifying fuel preferences and rising import taxes. The model is used to project the consequences of climate policy on energy security, and in fact scenarios show that climate policy has co-benefits that improve energy security. Possible benefits include reduced international trade, increased fuel diversity and slower depletion of fossil resources (PBL, 2012). This is shown in Figure 8.2.3 as trade is reduced as a consequence of climate policy, while trade in bioenergy increases. Analysis also shows that import restrictions mostly only have a temporary impact on energy security, leading to faster depletion of domestic resources, thus reducing long-term energy security (Kruyt et al., 2009).

Figure 8.2.2

Global household access to modern fuels for cooking and heating under a baseline scenario

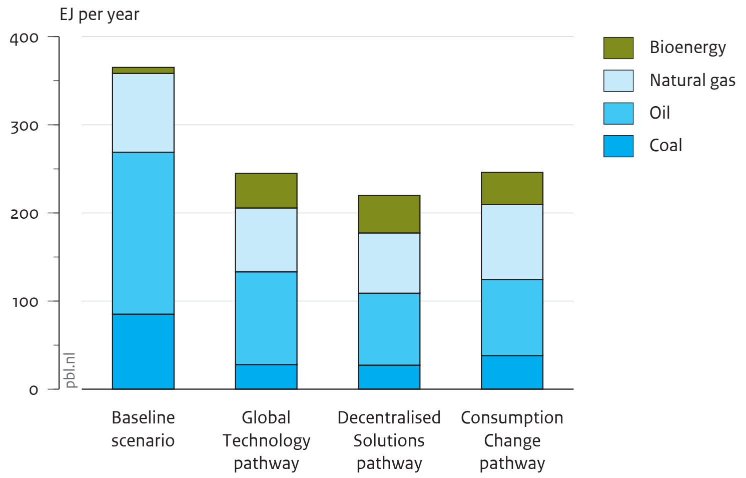


Source: PBL 2012

Under the baseline scenario, many more people gain access to modern fuels.

Energy access: Baseline developments
IMAGE can also be used to consider energy access issues. The baseline scenario of the Rio+20 report shows that without additional policy by 2030, 2.6 billion people will continue to depend on solid fuels for cooking and heating and 1 billion people will have no access to electricity (PBL, 2012) . Low energy access has been reported to lead to development issues and to environmental issues.

Figure 8.2.3
Global energy trade under the baseline and sustainability scenarios, 2050



Source: PBL 2012

Compared to the baseline, energy trade is significantly reduced under the sustainability scenarios (PBL, 2012).

Energy access: Policy interventions

The model defines access to modern energy sources for cooking and heating by either using modern fuels or improved biomass stoves. To make the transition, the IMAGE analysis include measures such as increased investments in the power grid (for access to electricity), fuel subsidies and grants, and micro-lending facilities for easier access to credit and lower borrowing costs for households (Van Ruijven et al., 2012). F or households for which the shift from biomass may still be out of reach under the induced financial policies, improved biomass stoves are distributed as a cost-effective interim solution. The Roads from Rio+20 report (PBL, 2012), for instance, explored measures, such as subsidies and grid extension, to achieve 95% grid connectivity and use of modern fuels for cooking and heating in 2030.

Air pollution: Baseline developments

Indoor and outdoor air pollution with negative health impacts are key issues for energy policies. IMAGE is used to explore air pollution policies, particularly in relation to climate policy. In the baseline scenario of the Rio+20 project, for instance, emissions of air pollutants remain at high levels globally (PBL, 2012) (see Figure 8.2.2). Black carbon emissions are projected to decrease towards 2050, while SO_2 emissions remain constant and NO_x emissions increase. Another key factor is the ageing population because the impacts of air pollution are felt stronger by the elderly.

Air pollution: Policy interventions
Emissions of air pollutants may be reduced by either a change in energy use or end-of-pipe abatement measures. In IMAGE, the first policy category can be modelled explicitly, for instance, as a result of climate policy. Many technologies that reduce greenhouse gas emissions also lead to less emissions of air pollutants. End-of-pipe policies can only be implemented by changing the emission factors (in an aggregated way). However, by relating the change in emission factors to those of more explicit air pollution models, it is possible to perform policy relevant experiments.

4. Data, uncertainties and limitations

Data
The quality and availability of data differ for energy security, access and air pollution. For energy security, data inputs to IMAGE are obtained indirectly by calibrating to IEA data for the historical period. Few global data are available for energy access. This implies that the model has been calibrated mostly to national data for key countries such as China and India, and then applied to all IMAGE regions. There are more inventories for air pollution emissions. Data for IMAGE are obtained from the EDGAR database.

Uncertainties and limitations
Another challenge is policy representation. Data on diverse energy policies are difficult to obtain, and several policies are not easily represented in a model. For instance, energy security policies often do not contain clearly formulated targets and associated policy instruments, but tend to be more abstract in the formulation of preferred directions combined with incentives for domestic production.

In IMAGE, assumptions and simplifications have been made to assess energy policies. A key issue, for instance, is the focus on centralised grids only. Decentralised and off-grid or mini-grid options may be preferable and more economical in rural regions. Similarly, for supplying heat, local alternatives may be attractive, such as locally produced biogas. For energy security, the key indicators in IMAGE are depletion, trade and diversity, while other aspects of energy security, such as accessibility and acceptability, are poorly represented.

As stated above, emission reduction measures for air pollution cannot be modelled explicitly. This has to be done by adjusting emission factors based on more detailed data. Air pollution policies are also not specified in terms of costs. The use of emission factors also implies that specific consequences, such as increases in other types of emissions and loss of energy efficiency, are difficult to address.

5. Key Publications

Kruyt B, Van Vuuren DP, De Vries HJM and Groenenberg H. (2009). Indicators for energy security. *Energy Policy* 37(6), pp. 2166–2181, DOI: 10.1016/j.enpol.2009.02.006.

Van Ruijven BJ, Schers J and Van Vuuren DP. (2012). Model-based scenarios for rural electrification in developing countries. *Energy* 38(1), pp. 386–397, DOI: 10.1016/j.energy.2011.11.037.

8.3 Land and biodiversity policies

Anne Gerdien Prins and Elke Stehfest

Key policy issues

- How can land-use policies contribute to strategies for halting biodiversity loss and reducing greenhouse gas emissions?
- How can changes in consumption patterns contribute to achieving sustainability goals through changes in land use?
- What are the synergies and trade-offs between halting biodiversity loss, food security, reducing nutrient emissions, and reducing water stress?

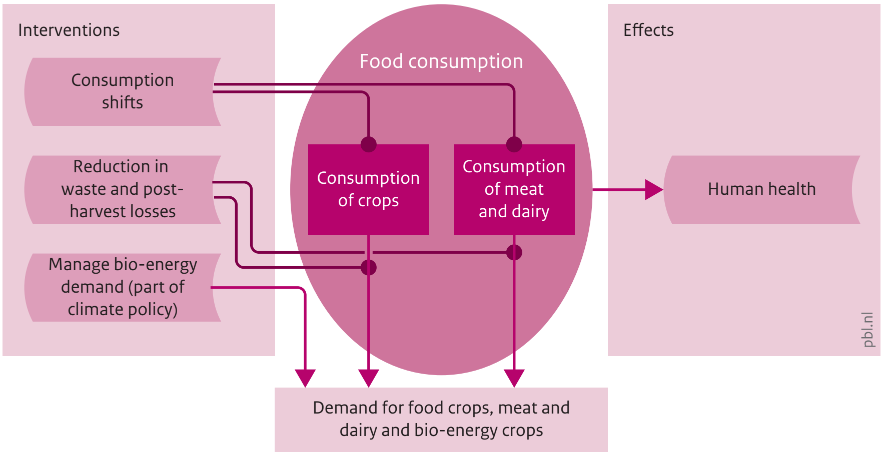
1. Introduction

The increase in material wealth, population and economic growth have led to a large demand for agricultural products and transformation of large parts of the land surface. The wide range of environmental issues related to agriculture and forestry include distorted nutrient balances, biodiversity loss, greenhouse gas emissions from land use and land-use change, soil degradation, and water stress due to agricultural water demand. These issues can be addressed from a sector perspective focusing on the respective system (e.g., nutrients, water, see the respective sections). However, these issues are linked by demand for land-based products, and by land management.

The IMAGE framework enables a systems approach to analyse policy interventions targeting the impacts of land use on biodiversity and climate change. To identify interventions that could reduce the impacts of agriculture and forestry on the environment, the system takes account of the chain linking demand for food, feed, wood, and bioenergy, to types of production systems and to landscape impacts.

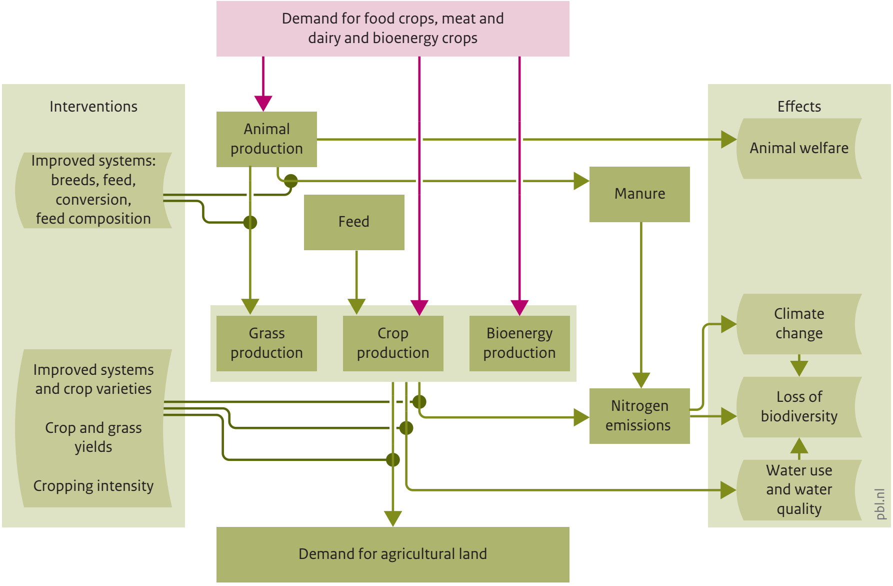
Policy interventions can target demand for commodities (Figure 8.3.1), the production system, for instance, with respect to efficiency of natural resource use (Figure 8.3.2 and 8.3.3), or a more systemic approach to regulating land use for different purposes within a landscape (Figure 8.3.4). Regulation of land use implies managing the land resource base by designating areas to specific purposes, such as excluding protected natural

Figure 8.3.1
Policy interventions in agricultural demand



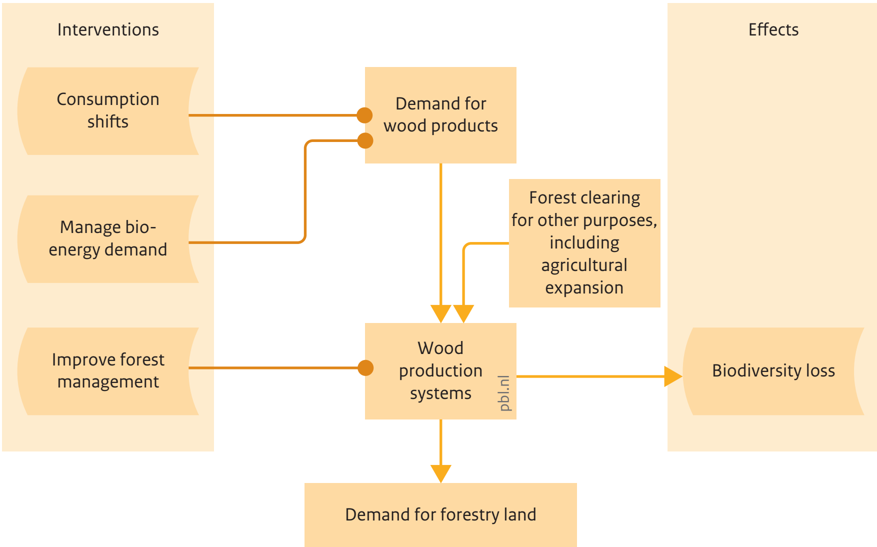
Source: PBL 2014

Figure 8.3.2
Policy interventions in the crop and livestock production systems



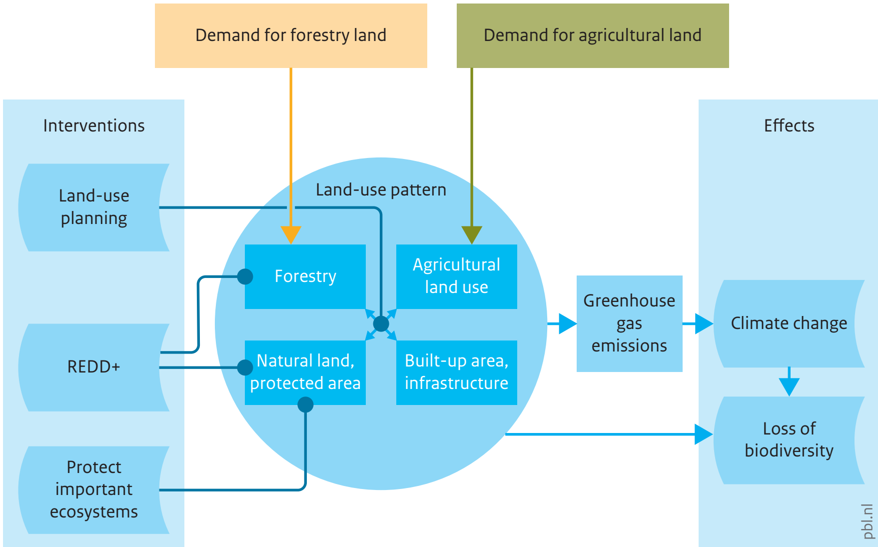
Source: PBL 2014

Figure 8.3.3
Policy interventions in the forestry system



Source: PBL 2014

Figure 8.3.4
Policy interventions in land-use regulation



Source: PBL 2014

areas from agricultural use, or preventing deforestation. Alternatively, regulation could be in the form of financial incentives to create value for currently non-market ecosystem services, such as emission reduction from deforestation combined with biodiversity conservation (e.g., REDD+ schemes) and other forms of payment for ecosystem services (PES).

While this section focuses on the impacts on biodiversity, climate change, water and nutrient balances, some policy interventions also have implications for other policy domains, such as food security, human health and animal welfare.

2. Model description

The interventions described in this section are implemented in different parts of the IMAGE 3.0 framework, and are also addressed in the sections in which the respective processes are described (see Table 8.3.1).

Policies that change **demand** for agricultural products are implemented in the agricultural economic model, thus taking into account the impacts on trade and demand in other regions. In IMAGE 3.0, change in wood demand is addressed in the model via a simple relationship with GDP, or by using external input data on wood demand (see Section 4.2.1). Demand for second-generation bioenergy crops is addressed in the energy model (see Section 4.1).

Changes in **production systems** are modelled in IMAGE using alternative input parameters. For the relevant inputs in e.g. the land-use allocation, livestock, and nutrient components (Sections 4.2.3, 4.2.4, 6.4), these changes are consistent with those in the agro-economic model (Section 4.2.1) , to ensure appropriate representation of the (cost) structure of production. Production system changes, for example those induced by taxes or scarcity of endowments, are implemented in the agro-economic model and adjusted in other components, accordingly.

Land-use regulation, which is the regulation of land supply, is modelled as a consistent resource constraint in the land-use allocation model (Section 4.2.3) and the agro-economic model (Section 4.2.1). This last model takes account of the economic effects of restricted land supply. For example, REDD+ and PES are implemented not as additional productive functions, but by reducing the land supply in the agro-economic model. The spatial dimension of such land-use regulation, like the expansion of protected area, is taken into account in the agricultural systems module, and affects via the resulting land use pattern all down-stream processes.

Table 8.3.1
Policy interventions for land and biodiversity in IMAGE 3.0

Intervention	Description and effect	Implemented in Section
Changes in agricultural demand		
Consumption shifts	Changes in diets (e.g., towards more or less meat consumption) affects all downstream impacts of agricultural demand as first-order effect	4.2.1
Manage bioenergy demand	Changes all downstream impacts of bio-energy demand as first-order effect. Short-term bioenergy demand is usually implemented in the agro-economic model, and long-term perspectives on bioenergy in the energy model TIMER.	4.1.3, 4.2.1
Reduction in waste and post-harvest losses	Reduces the required production, and thus reduces all downstream impacts of agricultural demand as first-order effect	4.2.1
Changes in production system		
Improved systems: breeds, feed, conversion, feed composition	More efficient feed use and feed composition reduces demand for feed	4.2.1, 4.2.4
Improved systems and crop varieties; crop and grassland yields; cropping intensity	Higher yields and cropping intensity reduce the area needed per unit of product, improved systems reduce the amount of water and nutrient required per unit of product	4.2.1, 6.2, 6.3
Forestry		
Consumption shifts	Changes all downstream impacts of wood demand as first-order effect	4.2.2
Manage bio-energy demand	Changes all downstream impacts of wood demand as first-order effect	4.1.3
Improve forest management	Higher productive plantations reduce the area needed per unit of product; reduced impact logging reduces the biodiversity loss per unit of product	4.2.2
Land-use regulation		
Land-use planning	Changes the availability of potential areas for agricultural or forestry	4.2.1, 4.2.3
REDD+, payments for ecosystem goods and services	Reduces the supply of potential agricultural and forest land, thereby reducing the amount of land conversion	4.2.1
Protect important ecosystems	Protecting certain areas against land conversion from nature to agriculture	4.2.1 4.2.3

A detailed list of all policy interventions that can be studied with IMAGE 3.0 is presented at www.pbl.nl/image

Agricultural demand

Interventions that induce **shifts in consumption,** for example to less meat-intensive diets, directly reduce the demand for animal products (Figure 8.3.1). As a first order effect, this intervention reduces all upstream effects of production proportionally. Thus, they lead to less demand for animal products and less demand for feed crop production, which in turns requires less land and water and fewer nutrients – if all other settings in the crop production system remain the same – and thus decrease the impacts on biodiversity and climate (Figures 8.3.2 and 8.3.3). However, as production systems are heterogeneous between and within regions, the effects may not be proportional. If, for example, extensively farmed agricultural areas, which typically have lower yields than other agricultural lands, are abandoned first, the area reduction will be larger. Likewise, if production shifts to regions with lower yields, less area reduction can be achieved.

In addition to this heterogeneity effect, feedbacks in the economic system via price and trade may change the final impact of a demand intervention, compared to the first-order effect, especially if such interventions are applied in certain regions only. Lower demand for meat may reduce world market prices, and thus increase demand in other regions (Stehfest et al., 2013). Although this rebound effect would reduce the environmental benefits of the intervention, the impact on food security could be positive.

Policies aimed at **reducing food losses,** either via reduced waste at the consumer level, or via reduced post-harvest losses decrease demand for food. This reduces the need to produce food crops, fodder crops and animal products and thus also reduces the environmental impacts of production systems and the area of agricultural land used. However, the same dynamics and second-order effects could be expected as those described under 'shifts in consumption'.

Policy interventions to manage **demand for bioenergy** directly change demand for bioenergy crops (Figure 8.3.1). The environmental impacts of such interventions, including land use, depend on the mix of bioenergy crops, and stimulation of and/or restrictions on bioenergy sources. Restricting the use of bioenergy directly affects the options and costs of climate policies (Section 8.1). The impact of reduced bioenergy demand on biodiversity can be twofold. More bioenergy requires more land and thus involves biodiversity loss (the same dynamics can be expected as under 'shifts in consumption'). However, if policy on bioenergy use is not replaced by other maybe more costly climate policy measures, long-term climate change would be more severe, and thus biodiversity loss due to climate change could also be greater (Oorschot et al., 2010).

Several policies that affect demand have been analysed using the IMAGE framework , for example, reduction in meat and dairy consumption (Stehfest et al., 2009; PBL, 2011; Stehfest et al., 2013), restricted use of bioenergy, and reductions in losses and waste (PBL, 2010; PBL, 2012).

Agricultural production system
The agricultural production system concerns how animals are raised and crops are cultivated. The characteristics of a particular system, for example what inputs are required to produce one unit of product, define the environmental impacts. Various interventions may increase the efficiency of production systems, and thus lead to reductions in inputs or in environmental impacts.

Interventions to **improve livestock systems** could include use of breeds that have higher feed conversion rates, require another ratio of feed composites, or produce less manure. Changes in feed conversion or feed composition, for example the ratio of grazing to feed crop feeding, have an impact on demand for grazing and cropland. Thus, changes to these systems will lead to other environmental impacts and other patterns of agricultural land use. For instance, quantity and quality of manure produced affect nitrogen emission levels and thus also nutrient balances and climate change impacts. In addition, biodiversity is affected by nitrogen emissions. Interventions can also be directed to improving animal welfare, but in most cases, higher animal welfare standards require more input per unit of production (PBL, 2011). Storage and application of manure varies with livestock systems, and affects crop yields and emission levels. A secondary impact of increasing feed efficiencies could be cost reductions, leading to a similar feedback effect as described for changes in demand.

Two interrelated interventions in the **cropping system** are distinguished: (i) : improved cropping systems or varieties; and (ii) increasing crop and grass yields or increasing cropping intensity (number of crops per year). Management in agriculture is an interplay of the cultivar chosen, soil management, fertiliser and other inputs, and the choice and timing of each cultivation step. The first interventions focus on reducing often negative external effects other than land use, and the second intervention targets the use of as small land areas as possible.

Improved cropping systems or varieties could increase the use efficiency of inputs including water and nutrients. Inputs fine-tuned to crop requirements would lead to less nitrogen emissions or less water use per tonne of crop and, would reduce the impacts on biodiversity and climate. While improved management could also lead to higher yields (see below), improved systems could mean a shift in inputs, such as labour, capital, land, fertiliser and water. This may alter the cost price of agricultural products, market prices and consumption.

Yields can be increased with other varieties, for example, to increase the potential yield, or with improved management (thus, close the yield gap). However, other, more suitable crop varieties often also need different types of management in order to produce higher yields.

Cropping intensity can be increased by multiple cropping (more harvests per year) depending on climatic conditions, or by decreasing the area left fallow. Both interventions would decrease the required production area for all crops but could also increase the environmental impacts per hectare of crops. Where lower area requirements decrease biodiversity and climate impacts, the environmental impacts per hectare could increase them again. Thus, to decrease biodiversity loss, yield increases need to go hand in hand with system changes to reduce external impacts. Increased cropping intensity increases the risk of soil degradation without adaptation of cropping rotations or soil management.

Results of an efficiency increase in livestock management are presented in the PBL report *The Protein Puzzle* (PBL, 2011; Stehfest et al., 2013). Alternative cropping practices are summarised in *Roads from Rio+20* (PBL, 2012).

Interventions targeting forestry

Interventions targeting **shifts in consumption** of forest products have a direct effect on timber demand, and thus also affect the need for forestry areas in production (PBL, 2010). The increase in demand could concern industrial roundwood or paper, but also wood as traditional bioenergy. As a first-order effect, an intervention to change demand for industrial products reduces all upstream effects of production proportionally. Data on wood for traditional biomass are not available, and estimates vary greatly partly due to whether the focus is on use or production. With estimates ranging from 1300 Mt/y (FAO, 2013a) to 2400 Mt/y (IEA, 2012a), a considerable proportion of the total wood use can be attributed to fuelwood. A decrease in wood use for traditional biomass has fewer direct impacts on the IMAGE biodiversity results than decreases in other uses, because only part of the production is harvested in industrial forestry activities (see Section 4.2.2). Large quantities of fuelwood are collected or produced in areas smaller than included in the level of detail of the IMAGE framework, such as orchards and road-sides. This implies that interventions related to this kind of use do not completely show up in biodiversity impacts.

Bioenergy demand will affect demand for forestry products for the energy sector, with effects similar to those expected under the shifts in consumption. The impact on biodiversity will depend on the sustainability criteria, management practices, and regions in which timber is harvested.

Improving **forest management** will affect the area required to meet timber demand and the impact of timber harvest on biodiversity loss. A system of Reduced Impact Logging (RIL), which relates to improvements that can be implemented in selective logging management, could reduce harvest damage, stimulate regrowth and maintain biodiversity (Putz et al., 2012). In addition, dedicated plantations could be established and would reduce the area of natural forest needed for timber harvest, since wood production is higher in plantation areas. However, biodiversity values of those areas are relatively low.

Reducing the rate of agricultural expansion can lead to fewer wood products from forest clearance / deforestation, and thus to an increase in the forest area to meet the wood demand (PBL, 2010); see also Section 4.2.2 Forest management. Options for alternative forest management have been evaluated in *Rethinking Global Biodiversity Strategies* (PBL, 2010).

Land-use regulation

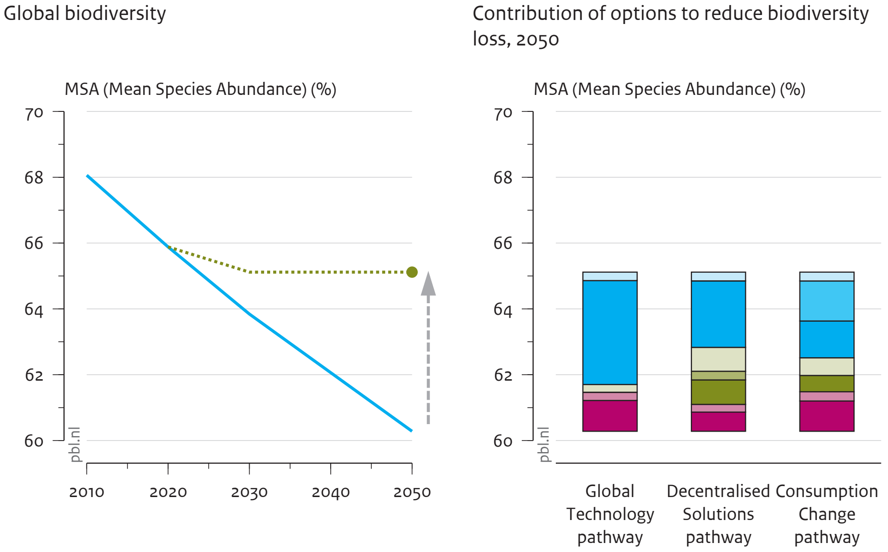
Demand and production technology determine the overall demand for agricultural and forestry land. However, land-use patterns and agricultural areas may also be influenced by regulating the land area available for specific purposes. Land allocation can be restricted in several ways.

Land-use planning directly affects the land-use pattern, which determines the impact on climate and biodiversity and could enhance the use of ecosystem functions. Measures, such as zoning plans and land registration, designate land areas to certain uses, including protected areas and natural corridors between designated agricultural land areas. The purpose of such natural corridors is to limit the impact on biodiversity of large agricultural areas and to connect individual spots rich in biodiversity. Restricting the land area for agriculture could affect land prices and prices of agricultural commodities with consequences for overall productivity and substitution of other production factors, such as labour and capital, and other inputs. Such interventions may result in changes to the production system (Figure 8.3.2) and the demand system (Figure 8.3.1), and in impacts on biodiversity and climate.

Some land uses that also provide ecosystem services could generate additional returns via **REDD+ schemes or payments for ecosystem services**. Such payments would place a value on ecosystem services that do not have a market value at present and would then compete with other economic activities for the same land area. This intervention would restrict the land available for agriculture or forestry, which would affect land prices and reduce consumption. This could induce adaptation in the production system (Figure 8.3.2), and consequently alter the impacts on biodiversity and climate at that level. The outcome of introducing payments for ecosystem services are currently most uncertain, as such schemes have not been applied frequently as yet.

Expansion of bio-reserves should increase biodiversity values, provided sites are well selected. The climate impact of these protection areas depends on the carbon content of the standing biomass. Most hot spots for biodiversity protection also have high carbon content (UNEP-WCMC, 2008). Furthermore, the impact of this intervention on agricultural production depends on the productivity level in these areas. Restricting the land area available for agriculture could affect land prices. Consequently, the same impacts as described under land-use planning could be expected. Expansion of bio-reserves has been analysed by PBL (PBL, 2010; PBL, 2012), and an evaluation of costs and CO_2 emission reductions via REDD+ schemes has been made by Overmars et al. (2012).

Figure 8.3.5
Global biodiversity under baseline and sustainability scenarios to prevent biodiversity loss



Biodiversity is projected to decline further in the baseline scenario (left). Various measures in the demand system, the production system and in land-use regulation contribute to reducing biodiversity loss in the sustainability scenarios (right).

3. Policy issues

Baseline developments
Components of the IMAGE framework that address land use and biodiversity include Agricultural economy (Section 4.2.1), Forest management (Section 4.2.2), Land-use allocation (Section 4.2.3) and Livestock system (Section 4.2.4).

Policy interventions
As described above, there is a large range of interventions that could affect land use and reduce biodiversity loss, which are introduced in the respective models in the IMAGE framework (mainly in Sections 4.2.1 to 4.2.4, see also Table 8.3.1).

Various studies have made a comprehensive analysis of potential land-use policies, using the IMAGE framework. For instance, the report *Rethinking Global Biodiversity Strategies* (PBL, 2010) shows that a combination of the interventions mentioned here may have sufficient potential to reverse the trend of biodiversity loss.

Roads from Rio+20 (PBL, 2012) formulated three packages of interventions to halt biodiversity loss by 2030 (Figure 8.3.5). The three sustainability scenarios differ fundamentally in approach and indicate that substantial efforts are needed in many areas. In all cases, increases in agricultural productivity are needed (Figure 8.3.5).

4. Data, uncertainties and limitations

Uncertainties

The type of analysis described in this section contains major uncertainties that increase with longer scenario periods. All processes involved are described in the respective model-specific section, together with the related uncertainties (see Table 8.3.1). The key uncertainties from a systems perspective are discussed here.

An uncertainty with regard to agricultural **demand** is the shift in consumption volume and consumption patterns due to higher incomes, cultural preferences and urbanisation. Although consumption per person is not likely not to exceed 4,000 kcal per person per day, the proportion of animal products in the diet and the types of products will largely determine the land area needed per person. Thus, a key uncertainty is the current transition to more animal products in the diet of an increasing proportion of the world population. In addition, the possible increase in biomass use for energy plays a key role in total demand.

In modelling **production systems,** the main uncertainties are developments in productivity and yield increases. Historically, yields have increased approximately 1% annually. However, increased production and yields result from development of new technologies and breeds, and from increased adoption of existing improved management practices, both partly driven by commodity prices. Empirical data and quantitative modelling of these intensification processes are still rather poor (Hertel, 2011). In addition, the agro-economy model does not cover farmer objectives and constraints. And research and plant breeding focus on decreasing susceptibility to water scarcity, diseases and pests, but it is uncertain whether more efficient varieties can be developed. New technologies to unravel crop DNA could significantly accelerate plant breeding process (Godfray et al., 2010).

The key uncertainty in **forestry** is the use of fuelwood and sources of traditional biomass, mostly due to limited data availability (Section 4.2.2). A substantial quantity of fuelwood is still used in developing countries, and how rapidly the shift to modern energy carriers will occur is highly uncertain (see also Section 8.2).

In **land-use regulation**, the effectiveness of protected areas is not always sufficient to maintain original biodiversity values (Leverington et al., 2010). IMAGE only takes account of economic processes in the agricultural sector but the complex socio-economic interactions that drive deforestation (Lambin et al., 2001) are not included. In addition, the role of national institutions in land use and land-use change is not included, although it is well known that these institutions largely define landscape and land use developments.

The uncertainty range changes with the time horizon of the scenario, and is greater for indicators further down the modelling chain. For example, biodiversity results are largely driven by land-use change, which is sensitive to uncertainties about land allocation and production systems, and to agricultural demand.

Limitations
The IMAGE framework may be used to analyse policy issues in different ways. Most frequently, technical interventions or assumed behavioural changes are implemented, and the results from alternative scenarios are used to answer ‘what if’ questions. However, the costs and policy measures to bring about such changes often cannot be modelled internally, and the feasibility of such options cannot be taken into account. Some economic instruments in the agro-economy model (e.g., a meat tax) can be modelled explicitly, and also specific policies, such as those on REDD+, biofuels, or additional protected areas, can be modelled explicitly for their economic and system-wide effects. Other important transitions, such as behavioural change cannot be modelled.

5. Key publications

PBL (2010). Rethinking global biodiversity strategies, B. ten Brink, S. Van der Esch, T. Kram, M. Van Oorschot, R. Alkemade, R. Ahrens, M. Bakkenes, J. Bakkes, M. Van den Berg, V. Christensen, J. Janse, M. Jeuken, P. Lucas, T. Manders, H. Van Meijl, E. Stehfest, A. Tabeau, D. Van Vuuren and H. Wilting. PBL Netherlands Environmental Assessment Agency Bilthoven/The Hague, www.pbl.nl/en/publications/2010/Rethinking_Global_Biodiversity_Strategies.

PBL (2011). The protein puzzle H. Westhoek, T. Rood, M. van den Berg, J. Janse, D. Nijdam, R. Melchert and E. Stehfest. PBL Netherlands Environmental Assessment Agency, Bilthoven/The Hague.

PBL (2012). Roads from Rio+20: Pathways to achieve global sustainability goals by 2050, D.P. Van Vuuren and M.T.J. Kok (eds.). PBL Netherlands Environmental Assessment Agency, Bilthoven/The Hague, www.pbl.nl/en/publications/2012/roads-from-rio20.

CONCLUDING REMARKS

9 Concluding remarks

Elke Stehfest, Tom Kram, Detlef van Vuuren

IMAGE 3.0

The history of the IMAGE model started in the late 1980s, and the current version 3.0 builds on many years of development at PBL and partner institutes. The model was originally constructed to assess the greenhouse gas effect on climate and was broadened in IMAGE2 to global environmental change. Later, the model was extended with advanced modelling of energy and agricultural systems. In IMAGE 3.0, further improvements were made, including representations of the energy and the agricultural systems, the carbon cycle, and crop growth. Other key elements were added in IMAGE 3.0, such as hydrology modelling and forest management. Geographic detail was increased by moving to a fine-scale land system representation, and impacts were extended with components on aquatic biodiversity, flood risks, and ecosystem services. This publication provides a complete overview of the IMAGE framework, model description and flow diagram of all components, and example results for baseline developments and policy applications. This transparent presentation of IMAGE, which is further expanded dynamically on the IMAGE website gives users insight into the model uncertainties and limitations, and its use in assessing policy issues.

The focus of IMAGE is on the representation of physical processes and geographic detail in the Human and Earth System. As a consequence, economic processes and feedbacks have received less attention.

The model's main areas of application are climate change and climate change mitigation, land use and biodiversity, and integrated scenario studies. Especially for the latter, IMAGE gives a broad view on global environmental change, and includes linkages to assess trade-offs, synergies and feedback mechanisms.

IMAGE is used in a large variety of studies ranging from global integrated assessments such as UNEP and OECD Environmental Outlooks, to sectoral assessments such as the Global Biodiversity Outlook, Global Energy Assessment, IPCC and the RCP and SSP process (see Section 1.6). One may conclude that this has been achieved by the emphasis on a broad and integrative view on sustainable development and global environmental change.

Challenges ahead

One of the tasks of integrated assessment models is to identify global environmental and sustainability issues now and for the future. While this will continue to be a key function of IMAGE, the focus will move increasingly towards identifying and assessing solutions and the impact on humans. While solution assessment is already advanced for climate policy, it is still early days for sustainability issues such as biodiversity loss and food security. Studies on the role of agricultural intensification and dietary change in mitigating climate change and biodiversity loss indicate the importance of such measures, but should move towards more explicit assessment of measures and policy instruments.

There is a growing interest in integration, trade-offs, and synergies in global environmental issues, reflected in terms of competing claims and food-water-energy nexus. This calls for closer linkages between IMAGE components. This integration needs to be well balanced with more focus on uncertainty. All IMAGE components are associated with substantial uncertainty, such as the effects of climate change on crop yields. However, further integration and more detail in single components can hamper accounting for the inherent uncertainty of all components and the linked framework. Many global models developed for climate, energy, vegetation or land use strive for further integration and broader focus, with more detailed process and geographic integration. Thus, the challenge will be to maintain IMAGE and other integrated assessment models at state-of-the-art, yet simple enough for the core task, the assessment of the long-term challenges and solutions for global sustainable development.

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REFERENCES

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In this book, we provide a complete and concise description of the IMAGE 3.0 integrated assessment model framework, and highlight how the model is used to assess key policy issues, such as climate change, air pollution, land-use change, biodiversity loss, and water scarcity. The IMAGE framework has been developed to understand how global, long-term environmental change and sustainability problems develop over time, driven by human activities, such as economic development and population growth. Similar to other integrated assessment models, IMAGE can be used to identify these problems and to advise on possible response strategies.

Over the last few years, earlier versions of the model have been used to support various international assessments, including IPCC assessments, UNEP's Global Environment Outlooks, OECD's Environmental Outlooks and the Millennium Ecosystem Assessment. In IMAGE 3.0, the descriptions of several critical areas of global environmental change have been improved, including the dynamics of land-use change, water use, and energy demand and production. This strengthens its relevance for addressing questions, such as how to reduce biodiversity loss and climate change, while safeguarding food and energy security.

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June 2014