



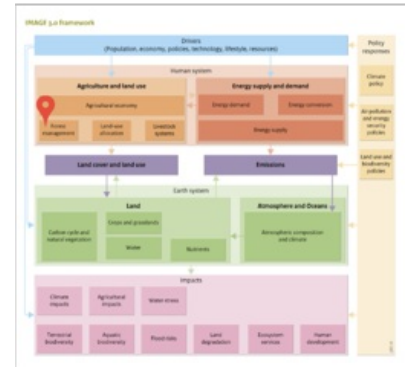
## Forest management

### Parts of Forest management

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Key policy issues
- 2 Introduction
- 3 Input/Output Table



### 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 biomass and 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?

### Introduction

The global forest area and wooded land area has been estimated for 2010 at just over 40 and 11 million km<sup>2</sup>, respectively (FAO, 2010). Forest resources are used for 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, the 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.

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 km<sup>2</sup>, somewhat larger than observed by FAO as this area includes fractions of other wooded land (see Component Carbon cycle and natural vegetation). 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).

1. 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.
2. 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 biodiversity levels (Putz et al., 2012).
3. 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, 2006b). By producing more wood products on less land, plantations may

### Related IMAGE components

- Drivers
- Land-use allocation
- Carbon cycle and natural vegetation
- Energy supply and demand

### Projects/Applications

- Rethinking Biodiversity Strategies (2010) project

### Models/Databases

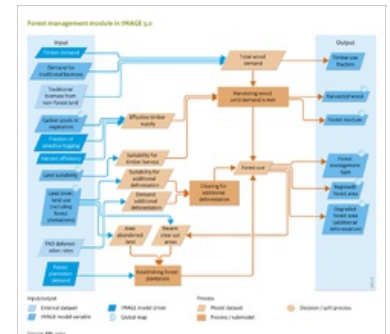
- FIGTM model

### Key publications

- Arets et al., 2011

### References

[Expand]



Flowchart Forest management. See also the Input/Output Table on the introduction page. The option of forest plantations in IMAGE and LPJmL is still under development, and expected to be available soon.

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).

Input/Output Table

Input Forest management component

IMAGE model drivers and variables	Description	Source
Forest plantation demand	Demand for forest plantation area.	Drivers
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.	Drivers
Harvest efficiency	Fraction of harvested wood used as product, the remainder being left as residues. Specified per biomass pool and forestry management type.	Drivers
Timber demand	Demand for roundwood and pulpwood per region.	Drivers
Carbon pools in vegetation - grid	Carbon pools in leaves, stems, branches and roots).	Carbon cycle and natural vegetation
Demand traditional biomass	Regional demand for traditional bioenergy.	Energy demand
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.	Land cover and land use
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.	Land-use allocation

External datasets	Description	Source
FAO deforestation rates	Historical deforestation rates according to FAO.	FAO
Traditional biomass from non-forest land	Fraction of traditional fuelwood from non-forestry sources, such as orchard, assumed to be 50% (low-income countries) and 68% (middle-income countries).	FAO

Output Forest management component

IMAGE model variables	Description	Use
Timber use fraction	Fractions of harvested timber entering the fast-decaying timber pool, the slow-decaying timber pool, or burnt as traditional biofuels.	> Carbon cycle and natural vegetation
Regrowth forest area - grid	Areas of re-growing forests after agricultural abandonment or timber harvest.	> Land cover and land use
Degraded forest area	Permanently deforested areas for reasons other than expansion of agricultural land (calibrated to FAO deforestation statistics).	> Land cover and land use
Harvested wood	Wood harvested and removed.	> Land cover and land use
Forest management type - grid	Forest management type: clear cut, selective logging, forest plantation or additional deforestation.	> Carbon cycle and natural vegetation > Land cover and land use
Forest residues	Harvest losses (from damaged trees and unusable tree parts) or harvest residues that are left in the forest by purpose because of environmental concerns. These losses/residues remains in the forest after harvest, in in principle enter the soil pools. But they could also be used for other/energy purposes.	Final output

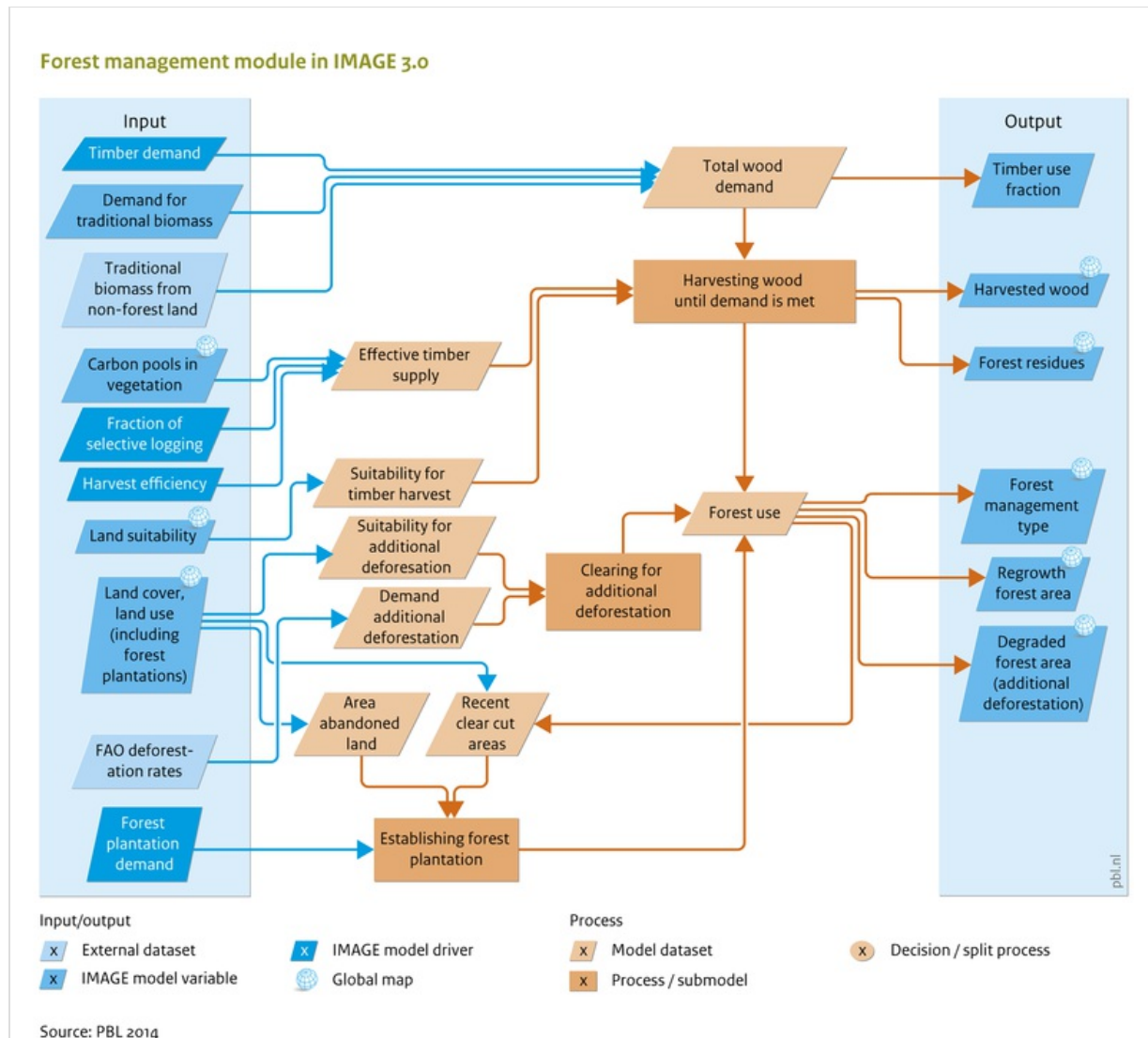
Parts of Forest management

- 1. Introduction page
- 2. Model description
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: Component



## Flowchart Forest management



Caption: Flowchart Forest management. See also the Input/Output Table on the introduction page. The option of forest plantations in IMAGE and LPJmL is still under development, and expected to be available soon.

Figure is used on page(s): Forest management

[View Image](#)

Category: Figure

[What links here](#) [Printable version](#) [Browse properties](#)



## Forest management/Description

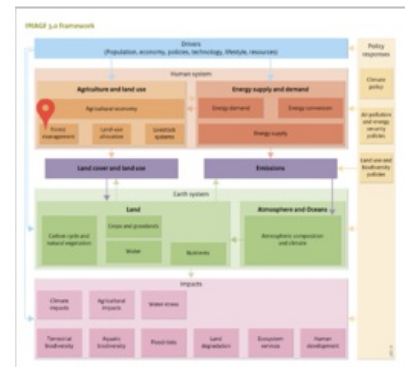
< Forest management

### Parts of Forest management

1. Introduction page
2. **Model description**
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Model description of Forest management
  - 1.1 Timber demand
  - 1.2 Timber supply & production in forests
  - 1.3 Selective logging
  - 1.4 Forest plantations
  - 1.5 Additional deforestation



### Model description of Forest management

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 deforestation.

#### 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 Component [Energy supply and demand](#)).

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 Flowchart). Firstly, timber is harvested in forests that have been converted to agriculture. Secondly, timber from forest plantations at the end of their rotation cycle are harvested. Finally, 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). This 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 is scenario driven (see also Input/Output Table at [Introduction](#) part),

### Related IMAGE components

- > [Carbon cycle and natural vegetation](#)
- > [Drivers](#)
- > [Energy supply and demand](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [Rethinking Biodiversity Strategies \(2010\) project](#)

### Models/Databases

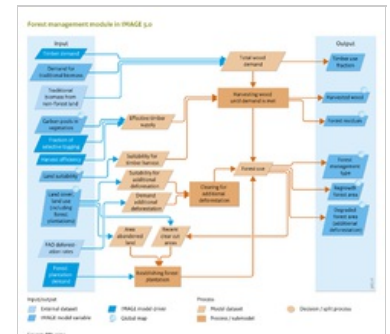
- > [EFIGTM model](#)

### Key publications

- > [Arets et al., 2011](#)

### References

[Expand]



Flowchart Forest management. See also the Input/Output Table on the introduction page. The option of forest plantations in IMAGE and LPJmL is still under development, and expected to be available soon.

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

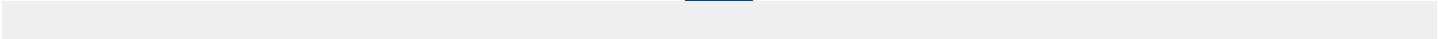
Globally, conversion to agricultural land is the major driver of forest clearing, and timber harvest does not result in deforestation, if natural vegetation is regrowing. But there are other causes of deforestation not related to food demand and timber production, such as urbanisation, mining and illegal 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.

Parts of Forest management

- 1. Introduction page
- 2. **Model description**
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: ComponentDescription

[What links here](#) [Printable version](#) [Browse properties](#)





## Forest management/Policy issues

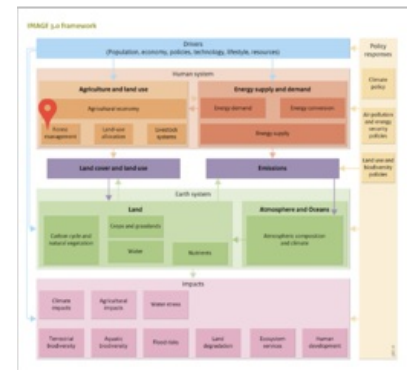
< [Forest management](#)

### Parts of Forest management

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

### Contents [\[hide\]](#)

- 1 Baseline developments
- 2 Policy interventions
- 3 Effects of policy interventions on this component



### 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 km<sup>2</sup>). The total forest area for wood production will increase from 9.5 to 14.5 million km<sup>2</sup> (the figure below, left panel). According to this projection, by 2050, just over a third of the global forest area will be used for wood production and consequently. In the same year, the area of primary forest, defined in IMAGE as established before 1970 and not exploited since, will decrease by more than 6 million km<sup>2</sup> from almost 30 million km<sup>2</sup> in 2000.

### Related IMAGE components

- > [Carbon cycle and natural vegetation](#)
- > [Drivers](#)
- > [Energy supply and demand](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [Rethinking Biodiversity Strategies \(2010\) project](#)

### Models/Databases

- > [EFIGTM model](#)

### Key publications

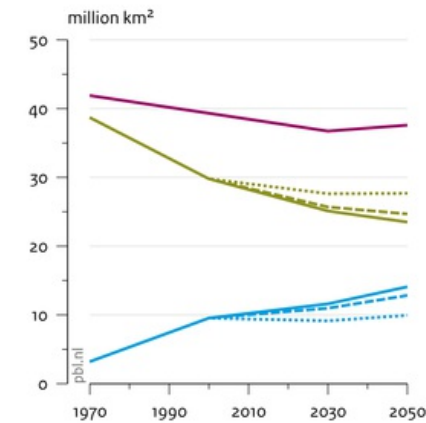
- > [Arets et al., 2011](#)

### References

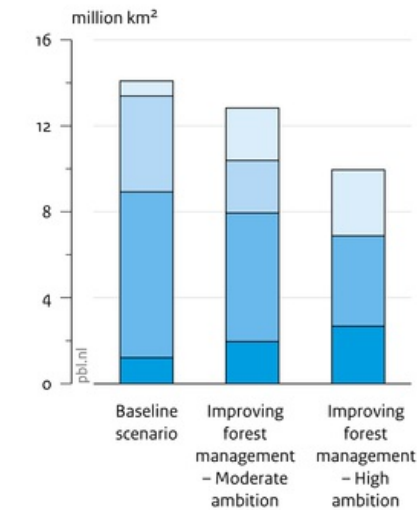
[\[Expand\]](#)

## Forests and forestry

### Primary forests and forestry



### Forestry, 2050



#### Total forest

— Baseline scenario

#### Primary forest

— Baseline scenario

- - - Improving forest management – Moderate ambition

..... Improving forest management – High ambition

#### Forestry

— Baseline scenario

- - - Improving forest management – Moderate ambition

..... Improving forest management – High ambition

#### Types of forest management

□ Reduced impact logging

□ Selective logging

□ Clear cut and regrowth

□ Plantations

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.



## Policy interventions

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

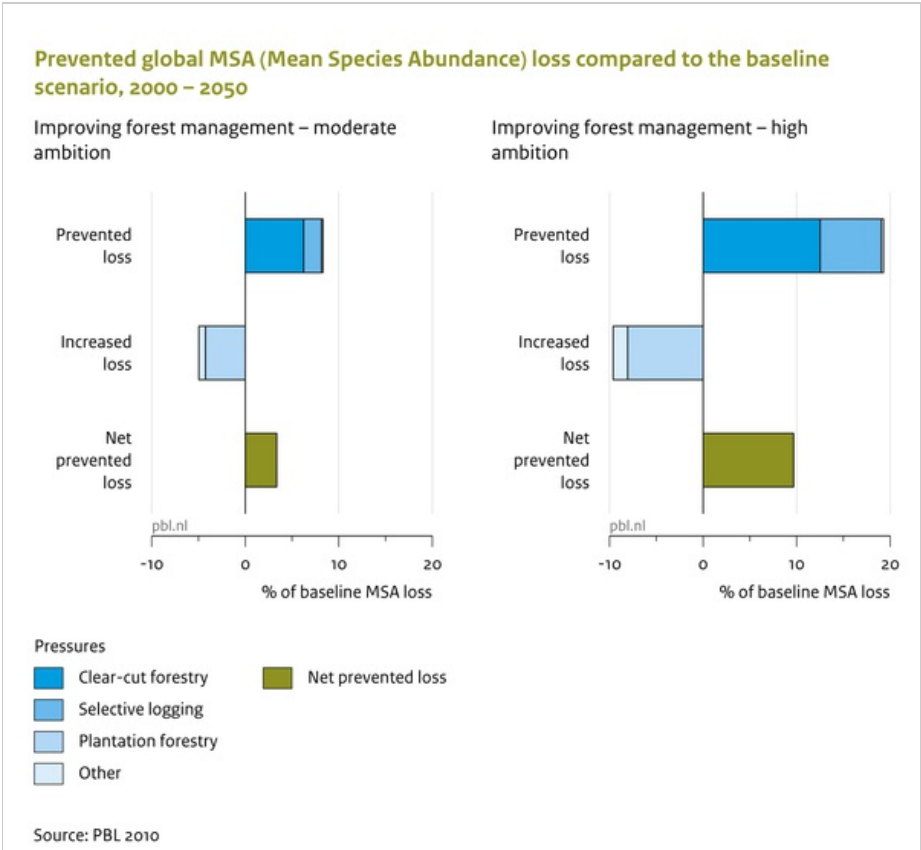
- > increase in production on highly productive forest plantations;
- > increase in carbon storage to mitigate climate change;
- > increasing harvest efficiencies, or using harvest residues for energy;
- > more reduced impact logging (RIL) techniques, less conventional selective felling.

The scenario study 'Rethinking global biodiversity strategies' implemented the following two ambition levels for improved forest management as alternatives for the baseline trend (the figures above and below):

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<sup>2</sup>, or one third smaller area than under the baseline scenario) (see the figure above). 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<sup>2</sup>, and less biodiversity loss prevented.





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

Effects of policy interventions on this component

Policy intervention	Description	Effect
Expanding Reduced Impact Logging (*)	Increasing the share of produced wood yielded with Reduced Impact Logging (RIL) practices instead of conventional logging practices. (Reference: PBL, 2010)	RIL leads to lower loss of biodiversity in forest areas, and it can have impacts on C pools and fluxes as less residues are produced per unit harvested wood product.
Increase forest plantations (*)	Increase the use of wood from highly productive wood plantations instead of wood from (semi-) natural forests. (Reference: PBL, 2010)	Decreases the area impacted by forestry/logging
More sustainable forest management (*)	Sustainable forest management aims for maintaining long-term harvest potential and good ecological status of forests (e.g. the nutrient balance and biodiversity). This can be implemented by (i) enlarging the return period when a forest can be harvested again; (ii) only using certain fractions of the harvested biomass and leave the remaining part in the forests.	Because forests might supply less timber, more sustainable forest management lead to more forests to be used throughout the world (assuming no change in demand).

(\*) Implemented in this component.

Parts of Forest management

- 1. Introduction page
- 2. Model description
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: ComponentPolicyIssue

What links here Printable version Browse properties





## Forest management/Data uncertainties limitations

< [Forest management](#)

### Parts of Forest management

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

### Contents [\[hide\]](#)

- 1 Data, uncertainties and limitations
  - 1.1 Data
  - 1.2 Uncertainties
  - 1.3 Limitations



### 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, 2012) 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, 2012), and fuelwood demand is only partly met by the forestry operations in this IMAGE module.

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.

### Related IMAGE components

- > [Carbon cycle and natural vegetation](#)
- > [Drivers](#)
- > [Energy supply and demand](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [Rethinking Biodiversity Strategies \(2010\) project](#)

### Models/Databases

- > [EFIGTM model](#)

### Key publications

- > [Arets et al., 2011](#)

### References

[\[Expand\]](#)

### Parts of Forest management

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**

Category: **ComponentDataUncertaintyAndLimitations**

[What links here](#) [Printable version](#) [Browse properties](#)





## Forest management/References

[< Forest management](#)

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E.J.M.M. Arets, P.J. van der Meer, C.C. Verwer, G.M. Hengeveld, G.W. Tolcamp, G.J. Nabuurs, M. van Oorschot (2011). Global wood production : assessment of industrial round wood supply from forest management systems in different global regions, Alterra Wageningen UR.

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R. Alkemade, M. Van Oorschot, L. Miles, C. Nellemann, M. Bakkenes, B. Ten Brink (2009). GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems*, 12(3), pp.374-390.

Link to PBL-website: <http://www.pbl.nl/en/publications/2009/GLOBIO3-A-Framework-to-investigate-options-for-reducing-global-terrestrial-biodiversity-loss>

#### ***Brown, 2000***

C. Brown (2000). The global outlook for future wood supply from forest plantations, Working Paper, FAO, Rome.

#### ***Carle and Holmgren, 2008***

J. Carle, P. Holmgren (2008). Wood from Planted Forests. *Forest Products Journal*, 58(12), pp.6-18.

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#### ***Hartmann et al., 2010***

H. Hartmann, G. Daoust, B. Bigué, C. Messier (2010). Negative or positive effects of plantation and intensive forestry on biodiversity: a matter of scale. *Forestry Chronicle*, 86(3), pp.354-364, doi: <http://dx.doi.org/10.5558/tfc86354-3> .

#### ***IEA, 2012***

IEA (2012). Global Wood Pellet Industry Market and Trade Study, International Energy Agency (IEA), Paris (URL: [www.data.iea.org](http://www.data.iea.org)).

#### ***Kallio et al., 2004***

A.M.I. Kallio, A. Moiseyev, B. Solberg (2004). The Global Forest Sector Model EFI-GTM - the model structure, EFI.

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#### ***Putz et al., 2012***

F. E. Putz, P. A. Zuidema, T. Synnott, M. Peña-Claros, M. A. Pinard, D. Sheil, J. K. Vanclay, P. Sist, S. Gourlet-Fleury, B. Griscom, J. Palmer, R. Zagt (2012). Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. *Conservation Letters*, 5(4), pp.296-303.

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Category: [AllReferencesPages](#)





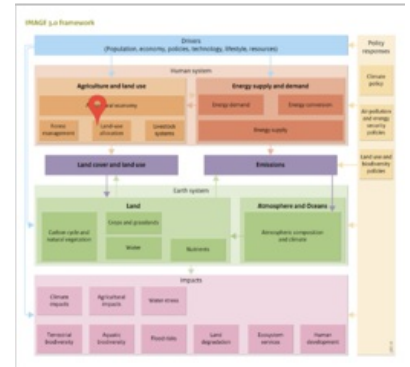
## Land-use allocation

### Parts of Land-use allocation

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Key policy issues
- 2 Introduction
- 3 Input/Output Table



### 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?

### 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. On the other hand, 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. 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 the IMAGE agro-economic model ([Agricultural economy](#)), by the potential crop and grass yields ([Crops and grass](#)), and suitability factors, applying two alternative methods.

### Input/Output Table

Input Land-use allocation component

IMAGE model drivers and variables	Description	Source
Increase in irrigated area - grid	Increase in irrigated area, often based on external projections (e.g., FAO).	Drivers
Population - grid	Number of people per gridcell (using downscaling).	Drivers
Protected area - grid	Map of protected nature areas, limiting use of this area.	Drivers

### Related IMAGE components

- Drivers
- Agricultural economy
- Crops and grass

### Projects/Applications

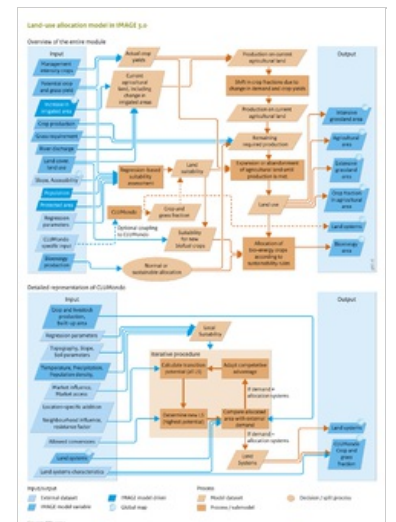
- Roads from Rio+20 (2012) project

### Implemented in computer model

- CLUMondo model
- IMAGE land use model

### Key publications

- Van Asselen and Verburg, 2012
- Verburg et al., 2013



Flowchart Land-use allocation. See also the Input/Output Table on the introduction page.

IMAGE model drivers and Variables	Description	Source
Bioenergy production	Total bioenergy production.	Energy supply, Energy supply and demand
Crop production	Regional production per crop.	Agricultural economy
Grass requirement	Grass requirement; ruminants (nondairy cattle, dairy cattle, sheep and goats) are grazing animals, and part (in mixed systems) or most (pastoral systems) of their feed is grass, hay or other roughage; this grass requirement is calculated as a fraction of the total energy (feed) requirement.	Livestock systems
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.	Land cover and land use
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.	Agricultural economy
Potential crop and grass yield - grid	Potential crop and grass yield, changing over time due to climate change and possibly soil degradation. In some components, i.e. 'Agricultural economy' regional aggregations of the dataset which depend on the actual land-use area, are used.	Crops and grass
River discharge - grid	Average flow of water through each grid cell.	Water

External datasets	Description	Source
Accessibility - grid	Accessibility expressed as travel time.	
CLUMondo specific input - grid	CLUMondo specific input.	
Other crops	Fraction of other, not modelled crops in agricultural area, assumed constant in the future.	FAOSTAT database
Regression parameters	Regression parameters of suitability assessment.	
Slope - grid	Terrain slope index.	IIASA

Output Land-use allocation component

IMAGE model variables	Description	Use
Crop fraction in agricultural area - grid	Fraction of agricultural land by crop type, per grid cell.	> Land cover and land use
Land systems - grid	Thirty land systems as defined in CLUMondo, characterized by specific levels of built-up area, cropland area, livestock density and management intensity.	> Land cover and land use
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).	> Land cover and land use
Extensive grassland area - grid	Extensive pasture with low productivity used for grazing.	> Land cover and land use
Agricultural area - grid	Total area for crop production (annual and perennial) and intensive grassland.	> Land cover and land use
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.	> Forest management
Intensive grassland area	Intensively used grassland areas for grazing or mowing, at locations also suitable for crop production.	> Land cover and land use

Parts of Land-use allocation

1. Introduction page
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

Category: Component



PBL Netherlands Environmental  
Assessment Agency

**IMAGE** *Integrated Model to Assess the Global Environment.*

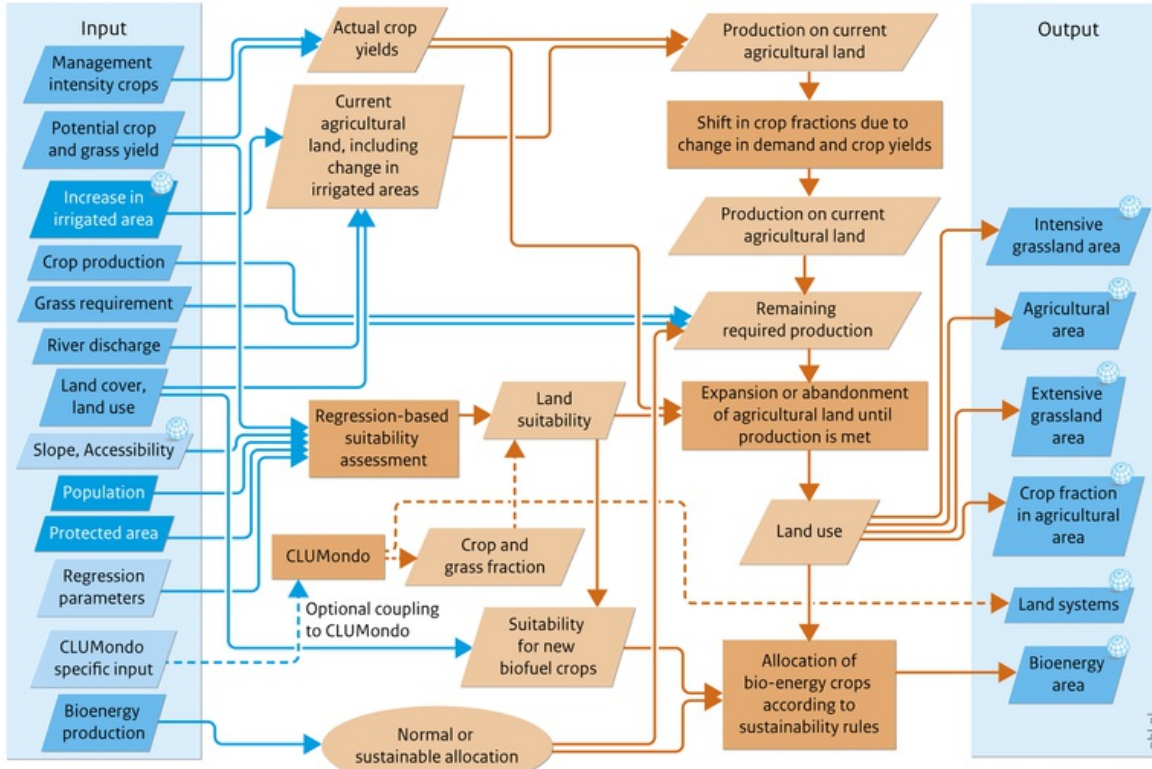
[Home IMAGE »](#) [IMAGE framework »](#) [Navigation »](#) [Browse wiki »](#) [About IMAGE »](#)

## Flowchart Land-use allocation

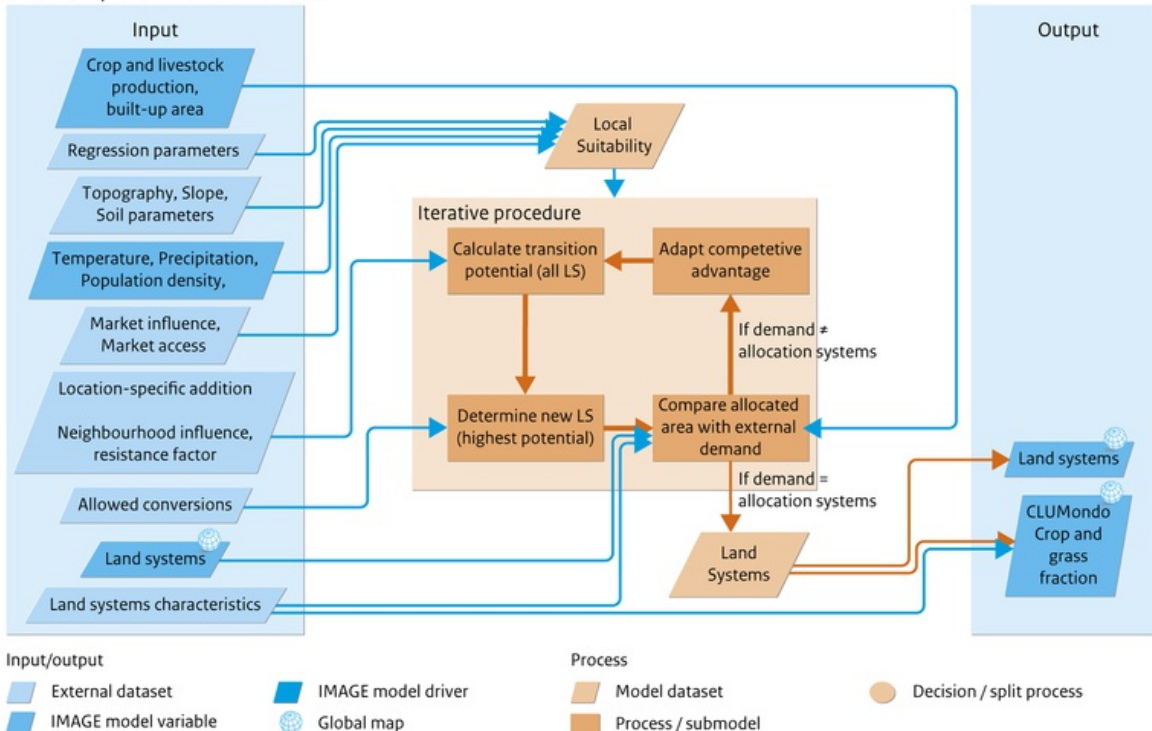


### Land-use allocation model in IMAGE 3.0

Overview of the entire module



### Detailed representation of CLUMondo



Source: PBL 2014

Caption: Flowchart Land-use allocation. See also the Input/Output Table on the introduction page.

Figure is used on page(s): Land-use allocation

[View Image](#)

Category: Figure

[What links here](#) [Printable version](#) [Browse properties](#)



## Land-use allocation/Description

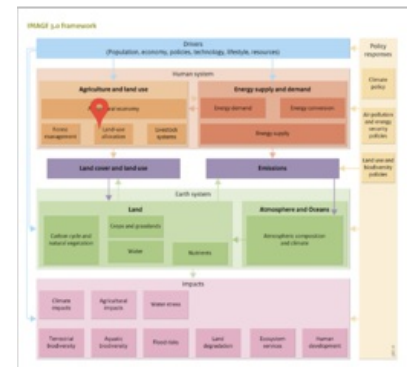
< [Land-use allocation](#)

### Parts of Land-use allocation

1. Introduction page
2. **Model description**
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [\[hide\]](#)

- 1 Model description of Land-use allocation
- 2 Empirical regression analysis to determine land use suitability
- 3 CLUMondo



### Model description of Land-use allocation

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, 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 (see flowchart).

Both approaches are driven by regional crop and grassland production and their respective intensity levels, as calculated by the IMAGE agro-economic model ([Agricultural economy](#)). 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 5 x 5 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 ([Crops and grass](#)), and the regional management intensity from the agro-economic model ([Agricultural economy](#)). 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

### Related IMAGE components

- > [Agricultural economy](#)
- > [Crops and grass](#)
- > [Drivers](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)

### Implemented in computer model

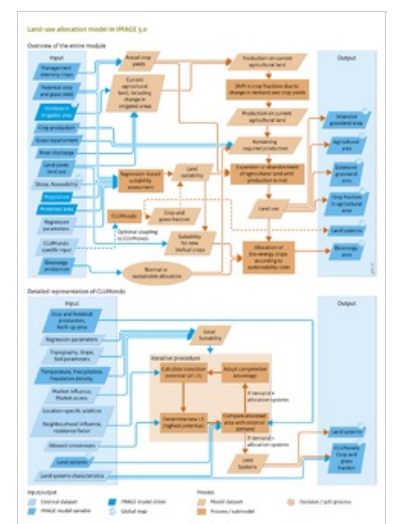
- > [CLUMondo model](#)
- > [IMAGE land use model](#)

### Key publications

- > [Van Asselen and Verburg, 2012](#)
- > [Verburg et al., 2013](#)

### References

[\[Expand\]](#)



Flowchart Land-use allocation. See also the Input/Output Table on the introduction page.

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.

The land use allocation model enables new land-use and land cover maps to be created (Land cover and land use). 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: and sugar cane, maize for bioenergy and woody and non-woody bioenergy). These data are calculated on a 5 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 [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. The suitability assessment includes data on two biophysical determinants: the potential yield which covers effects of climate and soil ([Crops and grass](#)), and the [terrain slope index](#) 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 5 x 5 minute resolution. In reality, land use is more heterogeneous. For some applications, dominant land use on 5 x 5 minute resolution, or the derived proportional land use on a 30 x 30 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., 2013](#)).

### CLUMondo

In cooperation with Wageningen University, the IMAGE team initiated the development of a more detailed land-use model ([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 (see figure).

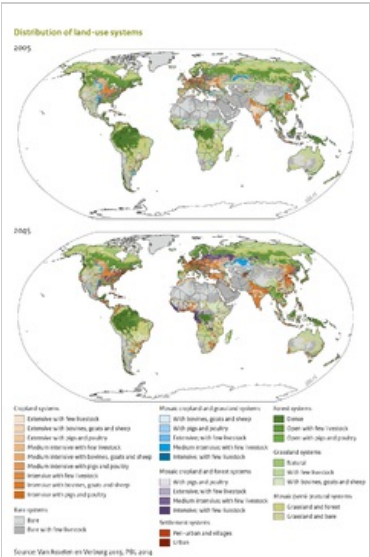
Logistic regressions between a range of biophysical and socioeconomic indicators, and the land systems are used to determine spatially explicit suitability for these systems. In combination with additional settings on neighbourhood effects, location-specific additions and a set of rules on conversion resistance, CLUMondo uses this suitability to model land system changes (see bottom flowchart). 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 30 x 30 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 (Agricultural economy). 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.

<b>Parts of Land-use allocation</b>
1. Introduction page
2. <b>Model description</b>
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references



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

Category: [ComponentDescription](#)

[What links here](#) [Printable version](#) [Browse properties](#)





## Land-use allocation/Policy issues

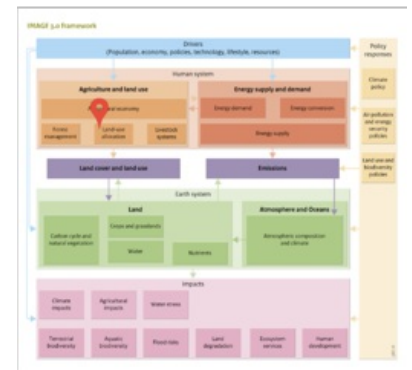
< [Land-use allocation](#)

### Parts of Land-use allocation

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

### Contents [\[hide\]](#)

- 1 Baseline developments
- 2 Policy interventions
- 3 Effects of policy interventions on this component



### Baseline developments

In a baseline scenario, agricultural area increases at the expense of forest and other natural areas (for instance, [PBL, 2012](#)). The land-use allocation model is used to indicate where these changes may occur (see figure below). Thus, it helps to assess the consequence of agricultural expansion and intensification in specific ecosystems.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Crops and grass](#)
- > [Drivers](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)

### Implemented in computer model

- > [CLUMondo model](#)
- > [IMAGE land use model](#)

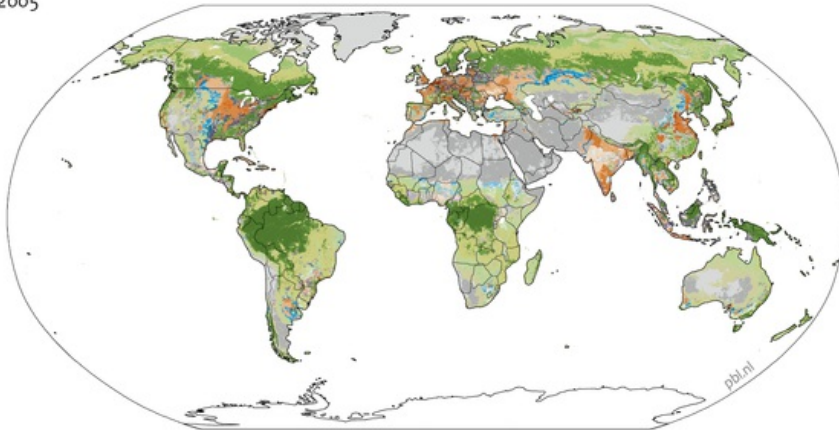
### Key publications

- > [Van Asselen and Verburg, 2012](#)
- > [Verburg et al., 2013](#)

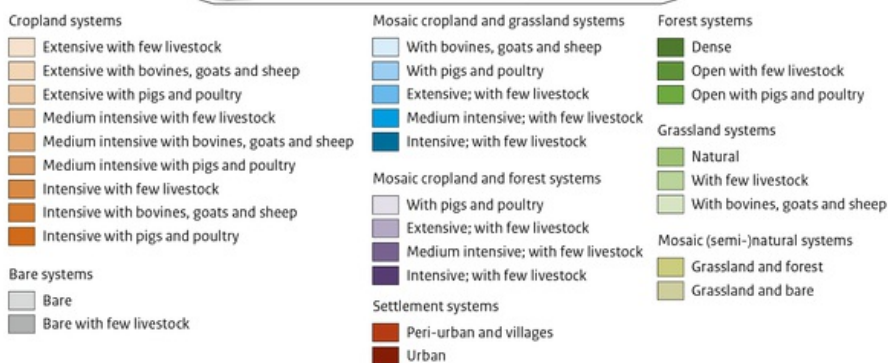
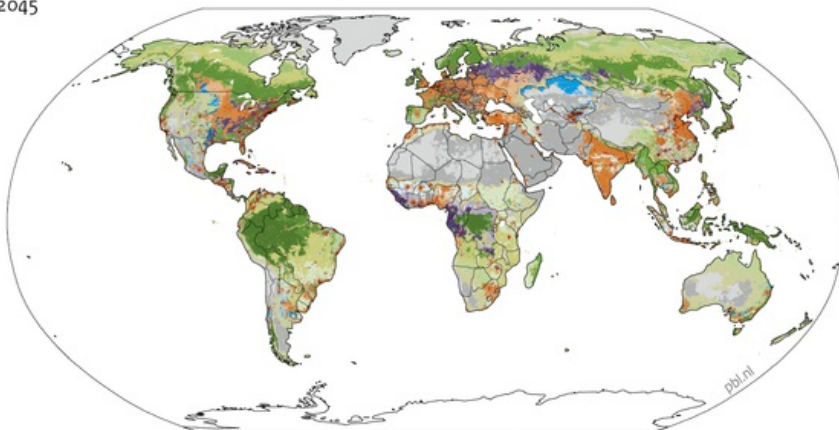


## Distribution of land-use systems

2005



2045



Source: Van Asselen en Verburg 2013, PBL 2014

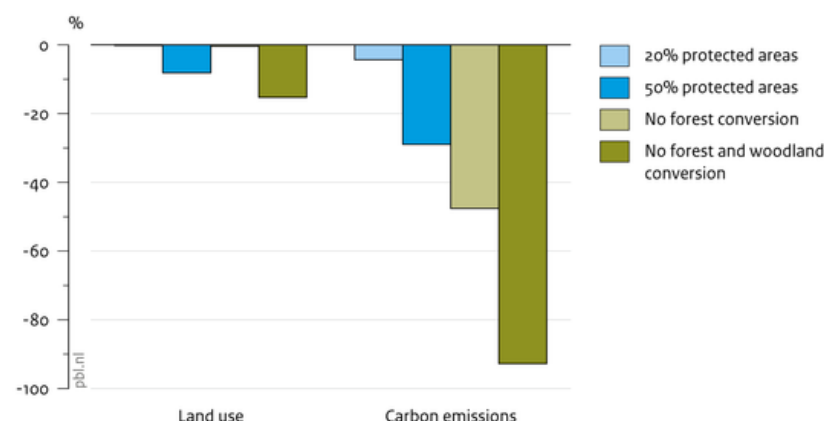
Dynamics of land-use expansion and intensification differ across regions.



## Policy interventions

The policy interventions that can be analysed are related to either the agricultural economy ([Agricultural economy](#)), or they are reflected in the allocation rules used in the land-use allocation module (e.g. more protected areas, [REDD+](#) schemes). In a study using the OECD Environmental Outlook scenario, the model 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% (Prot20) of 50% (Prot50) of the land area were protected as nature reserves, or that all forest and woodland was protected from agricultural expansion (see figure below). The relative reduction in land use and CO<sub>2</sub> 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<sub>2</sub> emissions are reduced, but reduction in land use and related biodiversity loss is much less.

### 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.

### Effects of policy interventions on this component

Policy intervention	Description	Effect
Agricultural trade policies	Changes in agricultural trade policies are applied to the corresponding quota (export or import quota) or border taxes. (Reference: <a href="#">Verburg et al., 2009</a> )	Due to changed production in agricultural commodities, land use for agriculture within a region will change.
Change in grazing intensity (*)	Change in grazing intensity, usually more intensive. This would require better management of grasslands, including for example the use of grass-clover mixtures and fertilisers, bringing the length of the grazing season in tune with the period of grass production, and rotations.	More intensive grassland management decrease the area needed for grassland, while producing the same amount of grass and/or feeding the same size of livestock.
Changes in consumption and diet preferences	Interventions that target consumption changes or changes in dietary preferences (Reference: <a href="#">Stehfest et al., 2013</a> )	Changes in production of agricultural commodities within a region change the land use for agricultural purposes (both total area for agriculture and the ratio of grass to crop area).
Enlarge protected areas (*)	Increase in areas with protected status, as well the size of the areas as the number of parks. (Reference: <a href="#">PBL, 2010</a> )	Agriculture is not allowed in protected areas and therefore is allocated at other locations.
Implementation of biofuel targets	Policies to enhance the use of biofuels, especially in the transport sector. In the Agricultural economy component only 'first generation' crops are taken into account. The policy is implemented as a budget-neutral policy from government perspective, e.g. a subsidy is implemented to achieve a certain share of biofuels in fuel production and an end-user tax is applied to counterfinance the implemented subsidy. (Reference: <a href="#">Banse et al., 2008</a> )	Targets for biofuel production/blending impact agricultural production and consequently land use.
Implementation of land use planning (*)	Application of zoning laws or cadastres, assigning areas to certain land uses.	Could affect allocation of agriculture, in case agriculture is excluded in some areas.
Increased livestock productivity	A change in production characteristics, such as milk production per animal, carcass weight and off-take rates, which will also have an impact on the feed conversion ratio; in general, this will be lower in more productive animals	A change in feed crop and grass requirements results in changes in land use, e.g. grasslands and cropping areas.
Intensification/extensification of livestock systems	A change in the distribution of the production over pastoral and mixed systems; usually to a larger share of the production in mixed systems, which inherently changes the overall feed conversion ratios of ruminants.	An intensification of livestock systems decreases the average area needed per animal (in land using livestock systems)
Reduction of waste/losses	Reduction of losses in the agro-food chain and waste after consumption. (Reference: <a href="#">PBL, 2010</a> , <a href="#">PBL, 2012</a> )	The reduced need for production decreases the need for agricultural area.

(\*) Implemented in this component.

#### Parts of Land-use allocation

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

Category: ComponentPolicyIssue







## Land-use allocation/Data uncertainties limitations

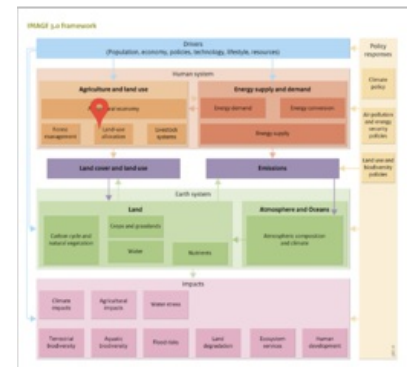
< [Land-use allocation](#)

### Parts of Land-use allocation

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

### Contents [\[hide\]](#)

- 1 Data, uncertainties and limitations
  - 1.1 Data
  - 1.2 Uncertainties
  - 1.3 Limitations



### 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 (Hurt et al., 2011). Other data sources include maps of protected areas (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.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Crops and grass](#)
- > [Drivers](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)

### Implemented in computer model

- > [CLUMondo model](#)
- > [IMAGE land use model](#)

### Key publications

- > [Van Asselen and Verburg, 2012](#)
- > [Verburg et al., 2013](#)

### References

[\[Expand\]](#)

### Parts of Land-use allocation

1. Introduction page
2. Model description

3. Policy issues

4. **Data, uncertainty and limitations**

5. Overview of references

Category: [ComponentDataUncertaintyAndLimitations](#)

[What links here](#) [Printable version](#) [Browse properties](#)





## Land-use allocation/References

< [Land-use allocation](#)

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S. Van Asselen, P.H. Verburg (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: <http://dx.doi.org/10.1111/gcb.12331>.

Category: AllReferencesPages

[What links here](#) [Printable version](#) [Browse properties](#)





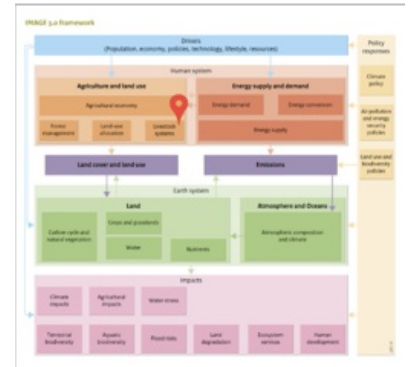
## Livestock systems

### Parts of Livestock systems

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Key policy issues
- 2 Introduction
- 3 Input/Output Table



### 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?

### 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 framework:

1. 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;
2. Large amounts of methane (CH<sub>4</sub>) emitted by ruminants during enteric fermentation are the second major source of greenhouse gas emissions after CO<sub>2</sub>;
3. Excreta from all livestock categories is a source of ammonia, methane, nitrous oxide and nitric oxide;
4. Odour nuisance and nitrate leaching to groundwater are major local-scale problems;
5. 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 overgrazing, 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.

### Input/Output Table

Input Livestock systems component

### Related IMAGE components

- > Drivers
- > Agricultural economy
- > Land-use allocation
- > Agriculture and land use
- > Atmospheric composition and climate
- > Crops and grass

### Projects/Applications

- > Roads from Rio+20 (2012) project
- > Global Environmental Outlook - GEO4 (2007) project
- > Millennium Ecosystem Assessment - MA (2005) project
- > OECD Environmental Outlook to 2030 (2008) project
- > OECD Environmental Outlook to 2050 (2012) project
- > Global Environmental Outlook - GEO3 (2002) project
- > EU Resource efficiency (2011) project

### Models/Databases

- > MAGNET model

### Implemented in computer model

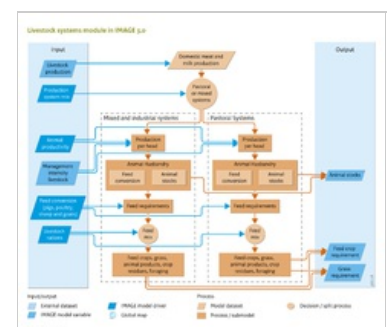
- > IMAGE land use model

### Key publications

- > Bouwman et al., 2005

### References

[Expand]



Flowchart Livestock systems. See also the Input/Output Table on the

IMAGE model drivers and variables	Description	Source
Animal productivity	Effective production of livestock commodities per animal per year.	Drivers
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).	Drivers
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).	Drivers
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.	Drivers
Livestock production	Production of livestock products (dairy, beef, sheep and goats, pigs, poultry).	Agricultural economy
Management intensity livestock	Management intensity of livestock, expressed at the regional level. This parameter is based on data and exogenous assumptions, i.e. current practice and technological change in livestock sectors, and is endogenously adapted within the Agricultural economy component.	Agricultural economy

## Output Livestock systems component

IMAGE model variables	Description	Use
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	> Emissions > Nutrients
Grass requirement	Grass requirement; ruminants (nondairy cattle, dairy cattle, sheep and goats) are grazing animals, and part (in mixed systems) or most (pastoral systems) of their feed is grass, hay or other roughage; this grass requirement is calculated as a fraction of the total energy (feed) requirement.	> Land-use allocation
Feed crop requirement	Total amount of feed required for the production of animal products. Grass and fodder species are consumed by grazing animals only (dairy and non-dairy cattle, sheep and goats), while pigs and poultry are fed feed crops and other feedstuffs.	> Emissions

## Parts of Livestock systems

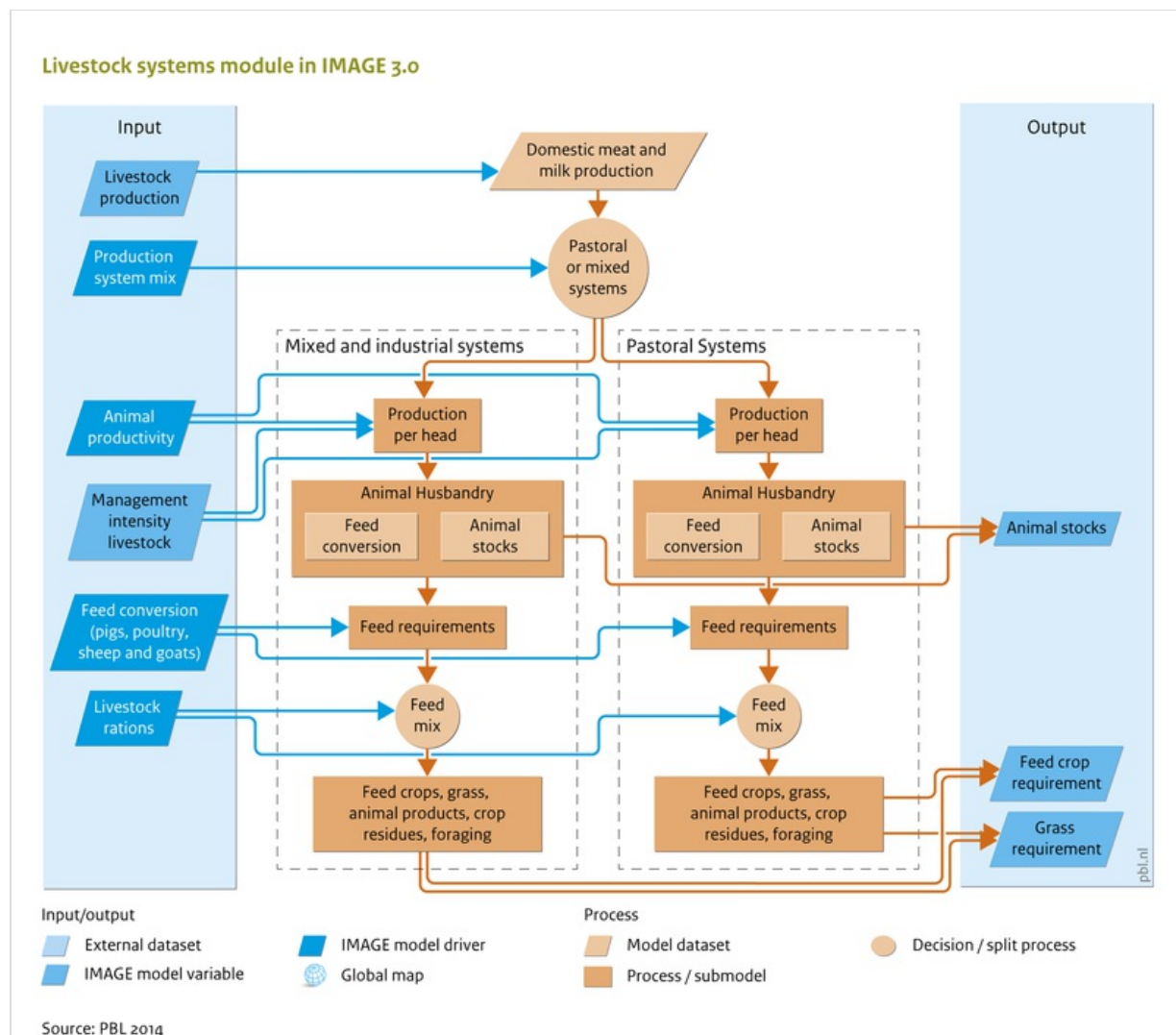
1. Introduction page
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

Category: Component

[What links here](#)
[Printable version](#)
[Browse properties](#)



## Flowchart Livestock systems



Caption: Flowchart Livestock systems. See also the Input/Output Table on the introduction page.

Figure is used on page(s): Livestock systems

[View Image](#)

Category: Figure

[What links here](#) [Printable version](#) [Browse properties](#)



## Livestock systems/Description

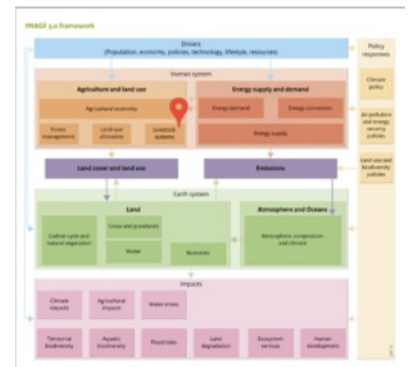
< [Livestock systems](#)

### Parts of Livestock systems

1. Introduction page
2. **Model description**
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [\[hide\]](#)

- 1 Model description of Livestock systems
- 2 Livestock production
- 3 Livestock
- 4 Energy requirements
- 5 Cropland and grassland required
- 6 Scenario definition



## Model description of Livestock systems

### Livestock production

IMAGE distinguishes two livestock production systems, 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 (large ruminants), the category sheep & goats (small ruminants), pigs, and poultry (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 ([Agricultural economy](#)). 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)

$$POP = PROD / MPH$$

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):

$$POP = PROD / (OR \cdot CW)$$

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 ([Land-use allocation](#)), which are calculated from total feed requirement and diet

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Atmospheric composition and climate](#)
- > [Crops and grass](#)
- > [Drivers](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [EU Resource efficiency \(2011\) project](#)
- > [Global Environmental Outlook - GEO3 \(2002\) project](#)
- > [Global Environmental Outlook - GEO4 \(2007\) project](#)
- > [Millennium Ecosystem Assessment - MA \(2005\) project](#)
- > [OECD Environmental Outlook to 2030 \(2008\) project](#)
- > [OECD Environmental Outlook to 2050 \(2012\) project](#)
- > [Roads from Rio+20 \(2012\) project](#)

### Models/Databases

- > [MAGNET model](#)

### Implemented in computer model

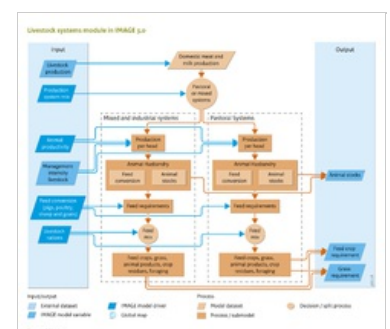
- > [IMAGE land use model](#)

### Key publications

- > [Bouwman et al., 2005](#)

### References

[\[Expand\]](#)



Flowchart Livestock systems. See also [\[Image\]](#)

composition (feed rations, see below). Composition of animal feed IMAGE distinguishes five feed categories:

- 1. grass, including hay and grass silage;
- 2. food crops and processing by-products;
- 3. crop residues in the field after harvesting, and fodder crops;
- 4. animal products;
- 5. 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 (Agricultural economy). 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 (Agricultural economy and Land-use allocation).

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, and on the economic growth scenario.

**Parts of Livestock systems**

- 1. Introduction page
- 2. **Model description**
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: ComponentDescription



the Input/Output Table on the introduction page.



## Livestock systems/Policy issues

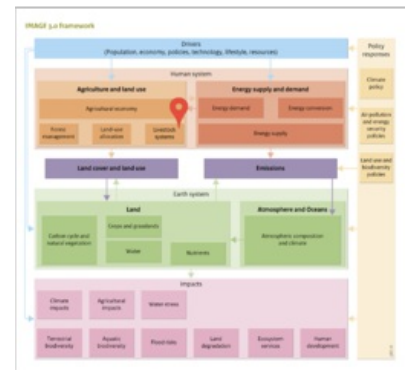
< [Livestock systems](#)

### Parts of Livestock systems

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

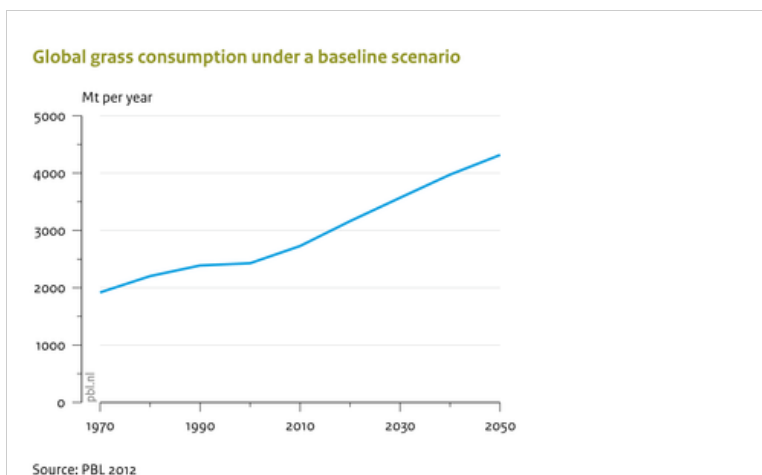
### Contents [\[hide\]](#)

- 1 Baseline developments
- 2 Policy interventions
- 3 Effects of policy interventions on this component



### Baseline developments

Between 1970 and 2010, global grass consumption increased by more than 40% (see figure below), while global grassland area only increased about 5% from 3134 to 3313 million hectares in the same period (see the figure in the policy intervention example section). 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 (see the figure in the policy intervention example section), but this will require considerable productivity increases in many parts of the world as discussed in [Bouwman et al., 2005](#).



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

### Policy interventions

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;
- > 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](#)

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Atmospheric composition and climate](#)
- > [Crops and grass](#)
- > [Drivers](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [EU Resource efficiency \(2011\) project](#)
- > [Global Environmental Outlook - GEO3 \(2002\) project](#)
- > [Global Environmental Outlook - GEO4 \(2007\) project](#)
- > [Millennium Ecosystem Assessment - MA \(2005\) project](#)
- > [OECD Environmental Outlook to 2030 \(2008\) project](#)
- > [OECD Environmental Outlook to 2050 \(2012\) project](#)
- > [Roads from Rio+20 \(2012\) project](#)

### Models/Databases

- > [MAGNET model](#)

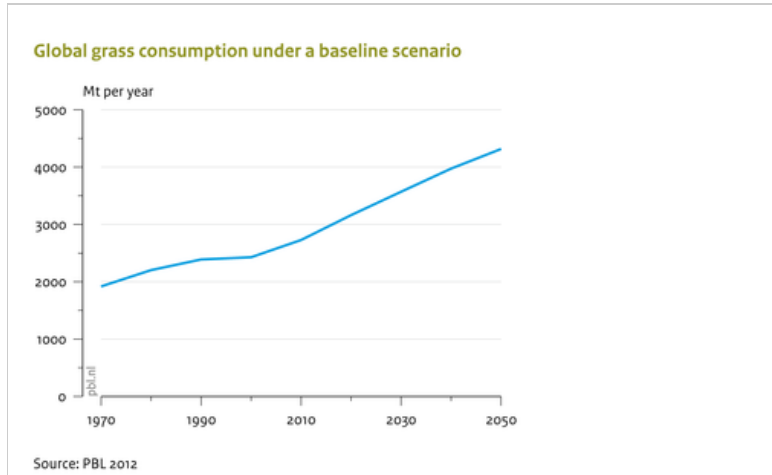
### Implemented in computer model

- > [IMAGE land use model](#)

### Key publications

- > [Bouwman et al., 2005](#)

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 (see figure below), leaving more area for biodiversity recovery.



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

Effects of policy interventions on this component

Policy intervention	Description	Effect
Change in grazing intensity	Change in grazing intensity, usually more intensive. This would require better management of grasslands, including for example the use of grass-clover mixtures and fertilisers, bringing the length of the grazing season in tune with the period of grass production, and rotations.	Increasing grazing intensity has no consequences for the livestock if not combined with introduction of better breeds
Changes in consumption and diet preferences	Interventions that target consumption changes or changes in dietary preferences (Reference: Stehfest et al., 2013)	Changes the production of livestock products within a region.
Changes in feed ration (*)	Change in the share of grass in the feed rations of cattle, sheep and goats, usually a decrease, meaning grass will be substituted by feed crops and the livestock system will be more intensive.	changes the grass and feed crop demand for the required livestock production.
Improvement of feed conversion (*)	Improvement of feed conversion ratio of small ruminants, such as sheep and goats. This means other breeds will be used that need less grass to produce the same amount of meat [CHECK!].	decreases the demand for grass.
Increased livestock productivity (*)	A change in production characteristics, such as milk production per animal, carcass weight and off-take rates, which will also have an impact on the feed conversion ratio; in general, this will be lower in more productive animals	Change the amount of feed crops and grass needed to feed animals.

(\*) Implemented in this component.

**Parts of Livestock systems**

- Introduction page
- Model description
- Policy issues**
- Data, uncertainty and limitations
- Overview of references

Category: ComponentPolicyIssue



## Livestock systems/Data uncertainties limitations

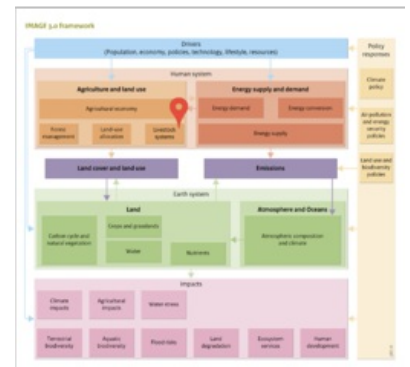
< [Livestock systems](#)

### Parts of Livestock systems

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

### Contents [\[hide\]](#)

- 1 Data, uncertainties and limitations
  - 1.1 Data
- 2 Uncertainties
- 3 Limitations



### 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](#) ([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](#)). [Seré and Steinfeld, 1996](#) also provided data on the growth in livestock populations and on production in each production system.

#### 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 (for example, 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 module, but also all impact IMAGE modules that depend on livestock numbers, such as ammonia emissions ([Beusen et al., 2008](#)).

The main uncertainties in construction scenarios concern agricultural demand ([Agricultural economy](#)), the distribution of production over the two systems, and production characteristics per system, including feed requirements and feed types.

#### Limitations

The key limitation in the current livestock module is that the ruminant livestock system have a soft linkage to the agricultural economy model MAGNET ([Agricultural economy](#)). 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.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Atmospheric composition and climate](#)
- > [Crops and grass](#)
- > [Drivers](#)
- > [Land-use allocation](#)

### Projects/Applications

- > [EU Resource efficiency \(2011\) project](#)
- > [Global Environmental Outlook - GEO3 \(2002\) project](#)
- > [Global Environmental Outlook - GEO4 \(2007\) project](#)
- > [Millennium Ecosystem Assessment - MA \(2005\) project](#)
- > [OECD Environmental Outlook to 2030 \(2008\) project](#)
- > [OECD Environmental Outlook to 2050 \(2012\) project](#)
- > [Roads from Rio+20 \(2012\) project](#)

### Models/Databases

- > [MAGNET model](#)

### Implemented in computer model

- > [IMAGE land use model](#)

### Key publications

- > [Bouwman et al., 2005](#)

### References

[\[Expand\]](#)

### Parts of Livestock systems

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references







## Livestock systems/References

< [Livestock systems](#)

### Key publications

#### ***Bouwman et al., 2005***

A.F. Bouwman, K.W. Van der Hoek, B. Eickhout, I. Soenario (2005). Exploring changes in world ruminant production systems. *Agricultural Systems*, 84(2), pp.121-153.

Link to PBL-website: <http://www.pbl.nl/en/publications/2005/Exploringchangesinworldruminantproductionsystems>

### All cited references

#### ***Beusen et al., 2008***

A. H. W. Beusen, A. F. Bouwman, P. S. C. Heuberger, G. Van Drecht, K. W. Van Der Hoek (2008). Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems. *Atmospheric Environment*, 42(24), pp.6067-6077.

Link to PBL-website: <http://www.pbl.nl/en/publications/2008/Bottom-up-uncertainty-estimate-of-global-ammonia-emissions-from-global-agricultural-production-systems>

#### ***Bouwman et al., 2005***

A.F. Bouwman, K.W. Van der Hoek, B. Eickhout, I. Soenario (2005). Exploring changes in world ruminant production systems. *Agricultural Systems*, 84(2), pp.121-153.

Link to PBL-website: <http://www.pbl.nl/en/publications/2005/Exploringchangesinworldruminantproductionsystems>

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A.F. Bouwman, K.W. van der Hoek, G. Van Drecht, B. Eickhout (2006). World livestock and crop production systems, land use and environment between 1970 and 2030. In: F. Brouwer, B. McCarl (eds.), *Rural Lands, Agriculture and Climate beyond 2015: A new perspective on future land use patterns*. Springer, Dordrecht, pp.75-

89, URL: <http://www.pbl.nl/en/publications/2006/Worldlivestockandcropproductionsystemslanduseandenvironmentbetween1970and2030>

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C. Delgado, M. Rosegrant, H. Steinfeld, S. Ehui, V.C. Courbois (1999). *Livestock to 2020. The next food revolution*, International Food Policy Research Institute, Food and Agriculture Organization of the United Nations, International Livestock Research Institute, Washington, D.C..

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Category: [AllReferencesPages](#)

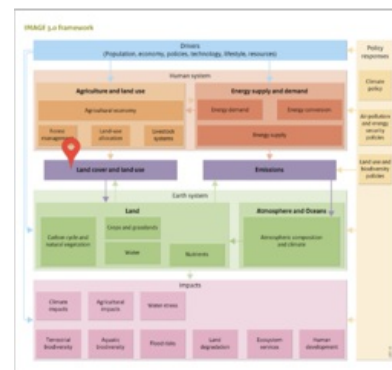
[What links here](#) [Printable version](#) [Browse properties](#)



## Land cover and land use

### Contents [hide]

- 1 Introduction
- 2 Model description
- 3 Input/Output Table



### 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, fertilizer 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.

### 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 (Input/Output Table below).

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](#), based on potential crop yields, protected areas, and external datasets such as slope, soil properties, and wetlands ([Mandryk et al., 2015](#)).

### Input/Output Table

Input Land cover and land use component

IMAGE model drivers and variables	Description	Source
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.	Drivers
Protected area - grid	Map of protected nature areas, limiting use of this area.	Drivers
Agricultural area - grid	Total area for crop production (annual and perennial) and intensive grassland.	Land-use allocation
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).	Land-use allocation
Carbon pools in soil and	Carbon biomass in three soil pools (litter, humus and charcoal) and two timber pools	Carbon cycle and natural

### Projects/Applications

> [Roads from Rio+20 \(2012\) project](#)

### Key publications

> [Mandryk et al., 2015](#)

IMAGE model drivers and variables	Description	Source
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).	Carbon cycle and natural vegetation
Carbon pools in vegetation - grid	Carbon pools in leaves, stems, branches and roots).	Carbon cycle and natural vegetation
Change in soil properties - grid	Change in soil properties, such as clay/sand content, organic carbon content, soil depth (topsoil/subsoil).	Land degradation
Crop fraction in agricultural area - grid	Fraction of agricultural land by crop type, per grid cell.	Land-use allocation
Degraded forest area	Permanently deforested areas for reasons other than expansion of agricultural land (calibrated to FAO deforestation statistics).	Forest management
Extensive grassland area - grid	Extensive pasture with low productivity used for grazing.	Land-use allocation
Forest management type - grid	Forest management type: clear cut, selective logging, forest plantation or additional deforestation.	Forest management
Harvested wood	Wood harvested and removed.	Forest management
Intensive grassland area	Intensively used grassland areas for grazing or mowing, at locations also suitable for crop production.	Land-use allocation
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.	Water
Land systems - grid	Thirty land systems as defined in CLUMondo, characterized by specific levels of built-up area, cropland area, livestock density and management intensity.	Land-use allocation
MSA (mean species abundance) - grid	Mean Species Abundance (MSA) relative to the natural state of original species.	Terrestrial biodiversity
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.	Agricultural economy
Management intensity livestock	Management intensity of livestock, expressed at the regional level. This parameter is based on data and exogenous assumptions, i.e. current practice and technological change in livestock sectors, and is endogenously adapted within the Agricultural economy component.	Agricultural economy
NPP (net primary production) - grid	CO <sub>2</sub> sequestered by plants and incorporated in new tissue in plant carbon pools.	Carbon cycle and natural vegetation
Potential natural vegetation - grid	Potential natural vegetation type/biome, based on distribution of plant functional types.	Carbon cycle and natural vegetation
Regrowth forest area - grid	Areas of re-growing forests after agricultural abandonment or timber harvest.	Forest management
Water withdrawal other sectors - grid	Total annual water withdrawal by non-agricultural sectors.	Water

#### Output Land cover and land use component

IMAGE model variables	Description	Use
Land supply for bioenergy - grid	Land available for sustainable bioenergy production (abandoned agricultural land and non-forested land).	> Energy supply
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.	> Agricultural economy
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.	> Aquatic biodiversity > Carbon cycle and natural vegetation > Crops and grass > Emissions > Flood risks > Forest management > Land degradation > Land-use allocation > Nutrients > Terrestrial biodiversity > Water

Category: Component

[What links here](#)
[Printable version](#)
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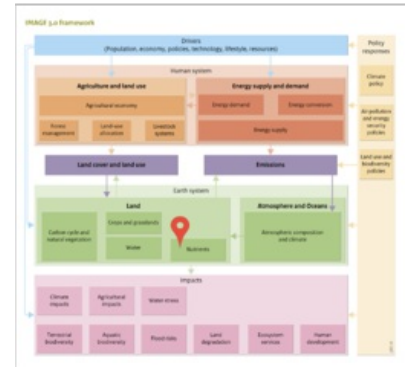
## Nutrients

### Parts of Nutrients

1. Introduction page
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Key policy issues
- 2 Introduction
- 3 Input/Output Table



### 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?

### 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<sub>3</sub>), nitrous oxide (N<sub>2</sub>O) 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.

To assess eutrophication as a consequence of increasing population, and economic and technological development, IMAGE 3.0 includes a nutrient model (Beusen, 2014), which comprises three sub-models:

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

### Input/Output Table

Input Nutrients component

### Related IMAGE components

- Drivers
- Agricultural economy
- Land-use allocation
- Agriculture and land use
- Aquatic biodiversity
- Emissions
- Land cover and land use
- Livestock systems

### Projects/Applications

- Roads from Rio+20 (2012) project
- Shared Socioeconomic Pathways - SSP (2014) project
- The Protein Puzzle (2011) project

### Implemented in computer model

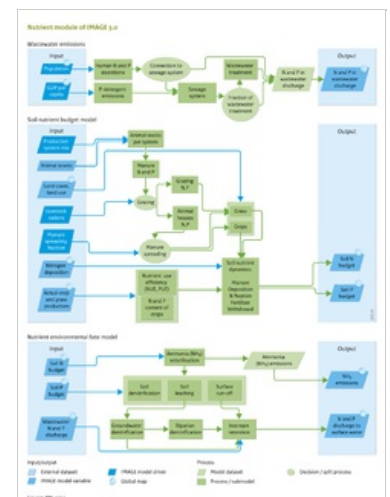
- IMAGE land use model

### Key publications

- Beusen, 2014
- Bouwman et al., 2013a
- Bouwman et al., 2009
- Morée et al., 2013

### References

[Expand]



Flowchart Nutrients. See also the



IMAGE model drivers and variables	Description	Source
Fertiliser use efficiency	Ratio of fertiliser uptake by a crop to fertiliser applied.	Drivers
GDP per capita - grid	Scaled down GDP per capita from country to grid level, based on population density.	Drivers
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).	Drivers
Manure spreading fraction	Fraction of manure produced in staples that is spread on agricultural areas.	Drivers
Population - grid	Number of people per gridcell (using downscaling).	Drivers
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.	Drivers
Actual crop and grass production - grid	Actual crop and grass production on agricultural land, based on potential yield and management intensity	Crops and grass
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	Livestock systems
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.	Land cover and land use
Nitrogen deposition - grid	Deposition of nitrogen.	Emissions

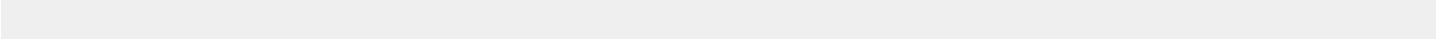
Output Nutrients component

IMAGE model variables	Description	Use
N and P discharge to surface water - grid	N and P discharge to surface water.	> Aquatic biodiversity
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
N and P in wastewater discharge - grid	Discharge of N and P to surface water from wastewater.	Final output
NH3 emissions - grid	Ammonia emissions from applied nitrogen fertiliser and manure.	Final output

Parts of Nutrients

- 1. Introduction page
- 2. Model description
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: Component





PBL Netherlands Environmental  
Assessment Agency

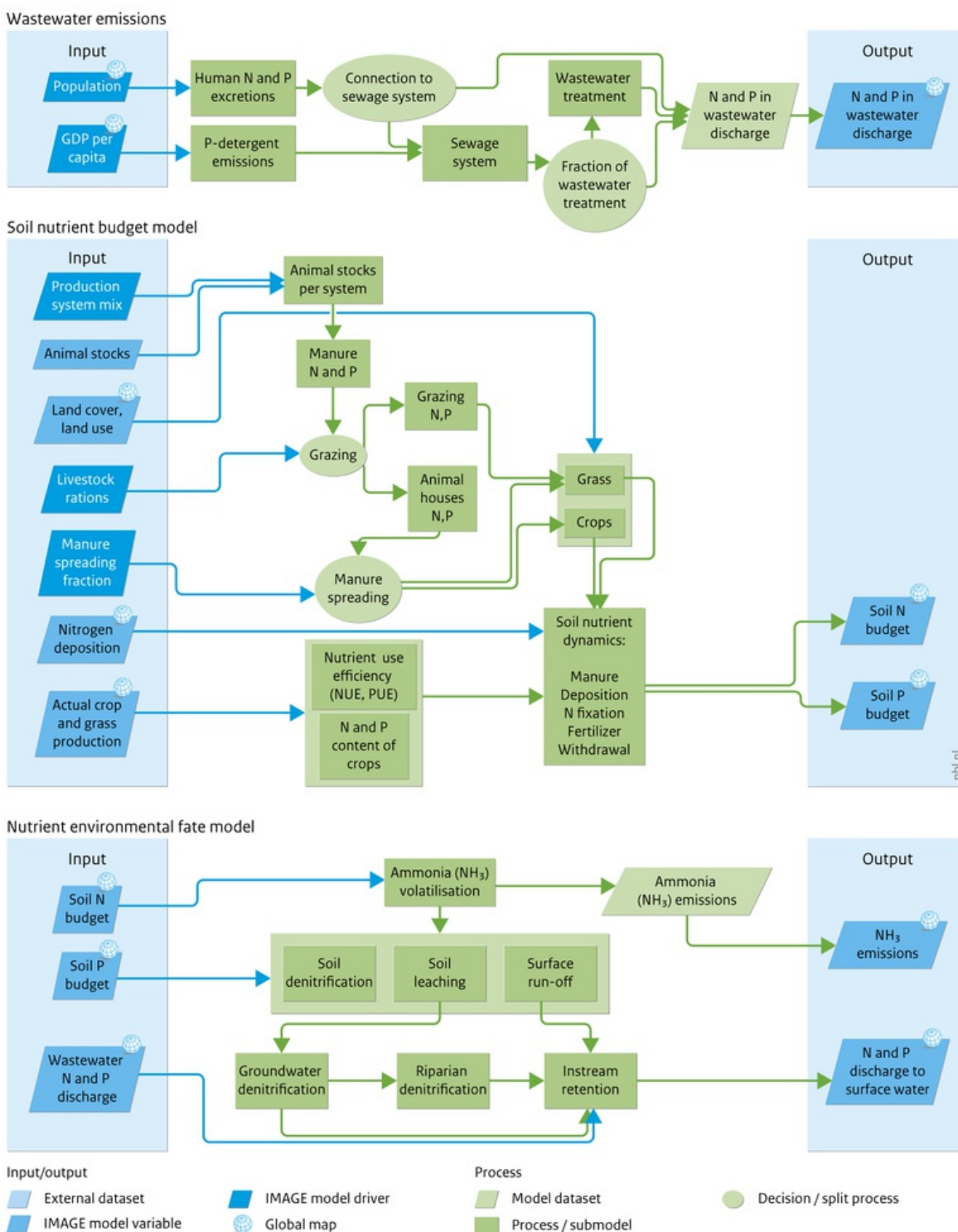
**IMAGE** *Integrated Model to Assess the Global Environment.*

[Home IMAGE »](#) [IMAGE framework »](#) [Navigation »](#) [Browse wiki »](#) [About IMAGE »](#)

## Flowchart Nutrients

Nutrient module of IMAGE 3.0



Source: PBL 2014

Caption: Flowchart Nutrients. See also the Input/Output Table on the introduction page.

Figure is used on page(s): Nutrients

[View Image](#)

(a) Wastewater nutrient model that generates N and P discharge to surface water; (b) Soil nutrient budget model; (c) Nutrient environmental fate model that describes N and P in the environment, including the pathways and processes of surface N and P runoff; soil denitrification; leaching of N to groundwater; groundwater transport and denitrification; denitrification in the riparian zone (the interface between land and streams or rivers); discharge to streams and rivers; N and P retention (in streams, rivers, lakes, wetlands and reservoirs).

Category: Figure





## Nutrients/Description

< [Nutrients](#)

### Parts of Nutrients

1. Introduction page
2. **Model description**
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Model description of Nutrients
  - 1.1 Wastewater
  - 1.2 Soil nutrient budget
    - 1.2.1 Fertiliser
    - 1.2.2 Manure
    - 1.2.3 Biological N<sub>2</sub> fixation
    - 1.2.4 Atmospheric deposition
    - 1.2.5 Nutrient withdrawal
  - 1.3 Nutrient environmental fate
    - 1.3.1 Soil denitrification and leaching
    - 1.3.2 Groundwater transport, surface runoff and denitrification
    - 1.3.3 Denitrification in riparian areas
    - 1.3.4 In-stream nutrient retention



### Model description of Nutrients

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

$$E_{sw}^N = E_{hum}^N D (1 - R^N)$$

where:

- >  $E_{hum}^N$  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:

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

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<sub>3</sub> volatilisation (see Component Emissions), denitrification, surface runoff and leaching. For P, this is surface runoff.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Aquatic biodiversity](#)
- > [Drivers](#)
- > [Emissions](#)
- > [Land cover and land use](#)
- > [Land-use allocation](#)
- > [Livestock systems](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)
- > [Shared Socioeconomic Pathways - SSP \(2014\) project](#)
- > [The Protein Puzzle \(2011\) project](#)

### Implemented in computer model

- > [IMAGE land use model](#)

### Key publications

- > [Beusen, 2014](#)
- > [Bouwman et al., 2009](#)
- > [Bouwman et al., 2013a](#)
- > [Morée et al., 2013](#)

### References

[Expand]



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 [Livestock systems](#)).

### 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 Flowchart, 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 Flowchart, 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<sub>2</sub> fixation

Data on biological N<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 N deposition field 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.

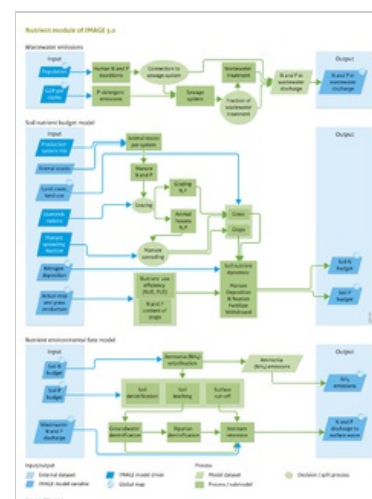
### Nutrient withdrawal

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<sub>3</sub> 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 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 Component [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



Flowchart Nutrients. See also the [Input/Output Table](#) on the introduction page.

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:

- 1. a biologically active layer of 0.3 m thickness is assumed instead of 1 m for other soils;
- 2. 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., 2014).

**Parts of Nutrients**

- 1. Introduction page
- 2. **Model description**
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: [ComponentDescription](#)

[What links here](#)   [Printable version](#)   [Browse properties](#)





## Nutrients/Policy issues

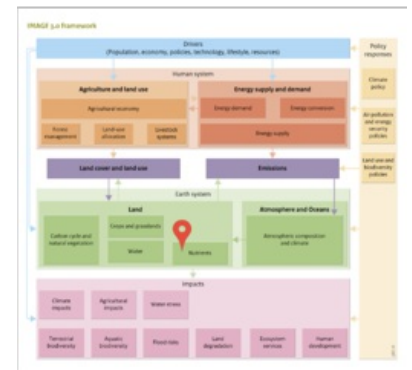
< [Nutrients](#)

### Parts of Nutrients

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

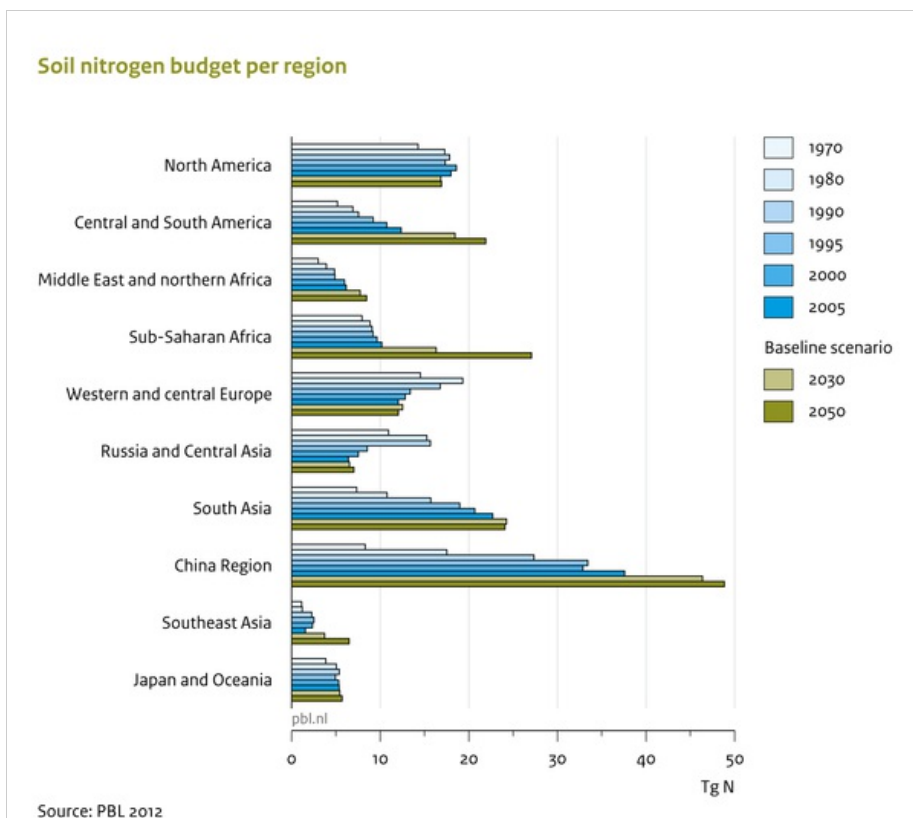
### Contents [hide]

- 1 Baseline developments
- 2 Policy interventions
- 3 Effects of policy interventions on this component



### 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 (the figure below). 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 fertilizer use to halt soil nutrient depletion (the figure below). The situation is similar for P, with large increases in developing countries.



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.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Aquatic biodiversity](#)
- > [Drivers](#)
- > [Emissions](#)
- > [Land cover and land use](#)
- > [Land-use allocation](#)
- > [Livestock systems](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)
- > [Shared Socioeconomic Pathways - SSP \(2014\) project](#)
- > [The Protein Puzzle \(2011\) project](#)

### Implemented in computer model

- > [IMAGE land use model](#)

### Key publications

- > [Beusen, 2014](#)
- > [Bouwman et al., 2009](#)
- > [Bouwman et al., 2013a](#)
- > [Morée et al., 2013](#)

budget (Formula 1, Model description part), and the fate of nutrients in the environment. For example, agricultural demand (Component [Agricultural economy](#)) 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 the figure below:

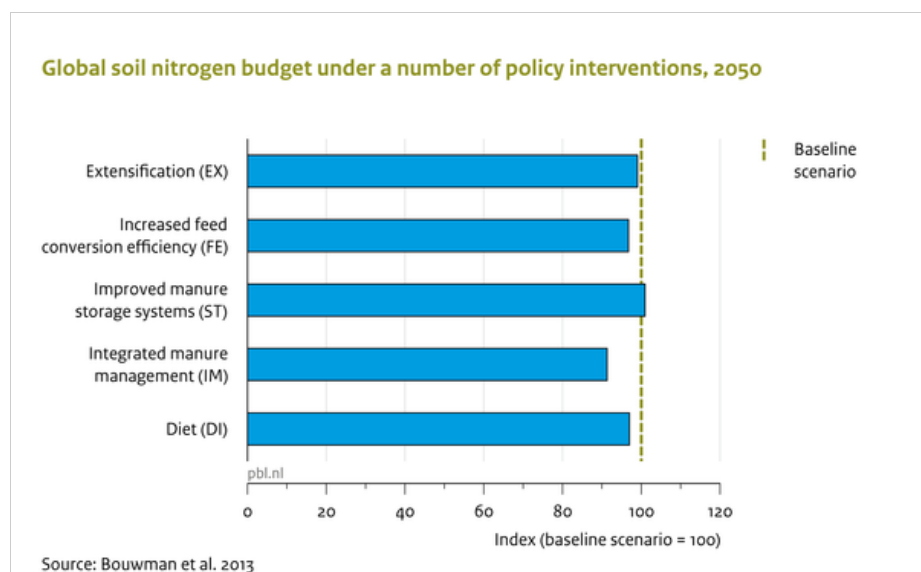
- > Extensification (EX), assuming for example that 10% of ruminant production in mixed and industrial systems shifts to pastoral production systems.
- > Increased feed conversion efficiency (FE), assuming for example 10% reduction in N and P excretion for cattle, pigs, poultry and small ruminants in mixed and industrial systems. This is achieved by increasing the use of concentrates.
- > Improved manure storage systems (ST), considering for example 20% lower  $\text{NH}_3$  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 the figure above) 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 (the figure below). 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.




See also Policy interventions Table below



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

## Effects of policy interventions on this component

Policy intervention	Description	Effect
Changes in consumption and diet preferences	Interventions that target consumption changes or changes in dietary preferences (Reference: Stehfest et al., 2013)	Dietary changes, for example assumes that by 2050 10% of the baseline scenario's beef consumption is replaced by poultry meat in all producing regions, without accounting for changes in agricultural trade

Policy intervention 	Description 	Without accounting for changes in agricultural trade 
Changes in crop and livestock production systems	General changes in crop and livestock production systems, e.g. more efficient production methods to create higher production per unit of input, or other systems like organic farming	intervention may be increased fertilizer use, or fertilizer use efficiency ...
Improved manure storage (*)	Improved manure storage systems (ST), considering 20% lower NH3 emissions from animal housing and storage systems.	This means that the animal manure that is used for spreading contains 5% more N than under the baseline scenario.
Improvement of feed conversion	Improvement of feed conversion ratio of small ruminants, such as sheep and goats. This means other breeds will be used that need less grass to produce the same amount of meat [CHECK!].	The increased use of concentrates effects the height of N and P excretion for cattle, pigs, poultry and small ruminants in mixed and industrial systems. In this example a 10% lower N and P excretion has been assumed.
Integrated manure management (*)	Better integration of manure in crop production systems. This consists of recycling of manure that under the baseline scenario ends up outside the agricultural system (e.g. manure used as fuel), in crop systems to substitute fertiliser. In addition, there is improved integration of animal manure in crop systems, particularly in industrialised countries.	This change causes more nutrients to be available for recycling in agriculture, and take nutrients in the manure into account when determining of the nutrient application rates
Intensification/extensification of livestock systems	A change in the distribution of the production over pastoral and mixed systems; usually to a larger share of the production in mixed systems, which inherently changes the overall feed conversion ratios of ruminants.	Generally leads to a reduction of overall emissions (e.g. CH4) and reduction of overall nutrient excretion; however, it will generally also lead to an increase of ammonia (NH3) emissions from manure storage and spreading of manure
Sanitation measures (*)	Increase the access to improved sanitation, and connection to sewage systems; institution of wastewater treatment installations; recycling of human waste for substitution of synthetic fertilisers.	This option has no consequences for nutrient budgets. Connection of inhabitants to sewage systems concentrates nutrient flows and generally leads to increasing pollution of surface water if not combined with wastewater treatment; Treatment results in a reduction of nutrient discharge.

(\*) Implemented in this component.

Parts of Nutrients

1. Introduction page

2. Model description

3. **Policy issues**

4. Data, uncertainty and limitations

5. Overview of references

Category: ComponentPolicyIssue

What links here

Printable version

Browse properties



## Nutrients/Data uncertainties limitations

< [Nutrients](#)

### Parts of Nutrients

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

### Contents [\[hide\]](#)

- 1 Data, uncertainties and limitations
  - 1.1 Data
  - 1.2 Uncertainties



## 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 (see Input/output Table Introduction part).

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, 2012b) 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<sub>3</sub> 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;
- > animal stocks.

### Related IMAGE components

- > [Agricultural economy](#)
- > [Agriculture and land use](#)
- > [Aquatic biodiversity](#)
- > [Drivers](#)
- > [Emissions](#)
- > [Land cover and land use](#)
- > [Land-use allocation](#)
- > [Livestock systems](#)

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)
- > [Shared Socioeconomic Pathways - SSP \(2014\) project](#)
- > [The Protein Puzzle \(2011\) project](#)

### Implemented in computer model

- > [IMAGE land use model](#)

### Key publications

- > [Beusen, 2014](#)
- > [Bouwman et al., 2009](#)
- > [Bouwman et al., 2013a](#)
- > [Morée et al., 2013](#)

### References

[\[Expand\]](#)

### Parts of Nutrients

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

Category: [ComponentDataUncertaintyAndLimitations](#)





## Nutrients/References

[< Nutrients](#)

### Key publications

#### **Beusen, 2014**

Beusen A.H.W. (2014). Transport of nutrients from land to sea: Global modeling approaches and uncertainty analyses. Ph.D thesis. Utrecht University. The Netherlands. URL: <http://dspace.library.uu.nl/handle/1874/298665>

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Link to PBL-website: <http://www.pbl.nl/en/publications/2009/Human-alteration-of-the-global-nitrogen-and-phosphorus-soil-balances-for-the-period-1970-2050>

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N.N. Rabalais (2002). Nitrogen in aquatic ecosystems. *Ambio*, 31(2), pp.102-112, doi: <http://dx.doi.org/10.1579/0044-7447-31.2.102>

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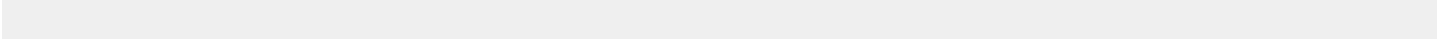
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J. Zhang, D. Gilbert, A. J. Gooday, L. Levin, S. W. A. Naqvi, J. J. Middelburg, M. Scranton, W. Ekau, A. Peña, B. Dewitte, T. Oguz, P. M. S. Monteiro, E. Urban, N. N. Rabalais, V. Ittekkot, W. M. Kemp, O. Ulloa, R. Elmgren, E. Escobar-Briones, A. K. Van der Plas (2010). Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. Biogeosciences, 7(5), pp.1443-1467.

Category: [AllReferencesPages](#)

[What links here](#)   [Printable version](#)   [Browse properties](#)





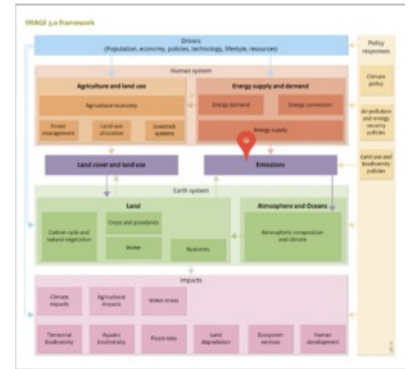
## Emissions

### Parts of Emissions

1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Key policy issues
- 2 Introduction
- 3 Input/Output Table



### 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?

### 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.

### Input/Output Table

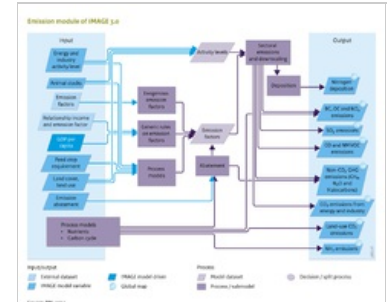
Input Emissions component

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)

### Key publications




- > [Van Vuuren et al., 2006](#)
- > [Braspenning Radu et al., submitted](#)
- > [Van Vuuren et al., 2011b](#)






Flowchart Emissions. See also the [Input/Output Table](#) on the introduction page. 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 (Emission Table).

IMAGE model drivers and variables	Description	Source
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.	Drivers
Animal stocks	Number of animals per category: non-dairy cattle; dairy cattle; pigs; sheep and goats; poultry.	Livestock systems
Emission abatement	Reduction in emission factors as a function of Climate policy.	Climate policy
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.	Energy conversion, Energy supply, Energy demand
Feed crop requirement	Total amount of feed required for the production of animal products. Grass and fodder species are consumed by grazing animals only (dairy and non-dairy cattle, sheep and goats), while pigs and poultry are fed feed crops and other feedstuffs.	Livestock systems
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.	Land cover and land use

External datasets	Description	Source
-------------------	-------------	--------

<b>External datasets</b> 	<b>Description</b> 	<b>Source</b> 
Emission factors	Exogenous emission factors per sector, activity and gas, mostly based on the EDGAR database.	EDGAR database
Relationship income and emission factor	Relationship between GDP and emission factors.	

Output Emissions component

<b>IMAGE model variables</b> 	<b>Description</b> 	<b>Use</b> 
Nitrogen deposition - grid	Deposition of nitrogen.	<div>&gt; Nutrients</div> <div>&gt; Terrestrial biodiversity</div>
CO and NMVOC emissions	Emissions from CO and NMVOC.	<div>&gt; Atmospheric composition and climate</div> <div>&gt; Climate policy</div>
CO2 emission from energy and industry	CO <sub>2</sub> emission from energy and industry.	<div>&gt; Atmospheric composition and climate</div> <div>&gt; Climate policy</div>
Non-CO2 GHG emissions (CH4, N2O and Halocarbons)	Non-CO <sub>2</sub> GHG emissions (CH <sub>4</sub> , N <sub>2</sub> O, Halocarbons).	<div>&gt; Atmospheric composition and climate</div> <div>&gt; Climate policy</div>
BC, OC and NOx emissions	Emissions of BC, OC and NO <sub>x</sub> per year.	<div>&gt; Atmospheric composition and climate</div> <div>&gt; Climate policy</div> <div>&gt; Human development</div>
SO2 emissions	SO <sub>2</sub> emissions, per source (e.g. fossil fuel burning, deforestation).	<div>&gt; Atmospheric composition and climate</div> <div>&gt; Climate policy</div> <div>&gt; Human development</div>

Parts of Emissions

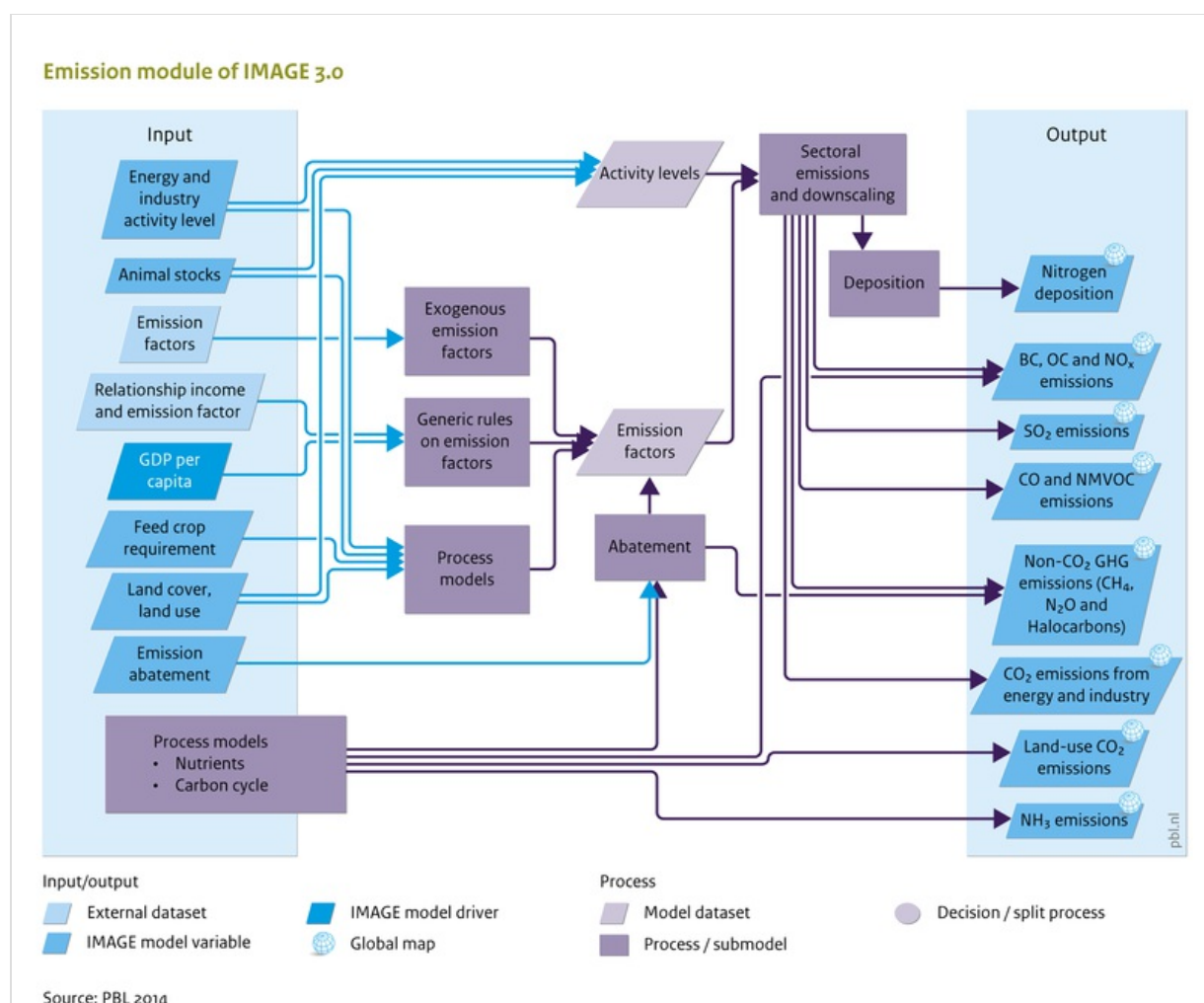
1. **Introduction page**
2. Model description
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references

Category: **Component**

[What links here](#) [Printable version](#) [Browse properties](#)



## Flowchart Emissions



Caption: Flowchart Emissions. See also the Input/Output Table on the introduction page. 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 (Emission table).

Figure is used on page(s): Emissions

[View Image](#)

Category: Figure

[What links here](#) [Printable version](#) [Browse properties](#)



## Emissions/Description

< Emissions

### Parts of Emissions

1. Introduction page
2. **Model description**
3. Policy issues
4. Data, uncertainty and limitations
5. Overview of references
- Additional info
6. Emission table

### Contents [hide]

- 1 Model description of Emissions
  - 1.1 General approaches
  - 1.2 Emissions from energy production and use
  - 1.3 Emissions from industrial processes
  - 1.4 Land-use related emissions
  - 1.5 Emission abatement



## Model description of Emissions

### General approaches

Air pollution emission sources included in IMAGE are listed in [Emission table](#), and emissions transported in water (nitrate, phosphorus) are discussed in Component [Nutrients](#). In approach and spatial detail, gaseous emissions are represented in IMAGE in four ways:

#### 1) 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 ([Emission table](#)).

#### 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 Flowchart).

The equation for this emission factor approach is:

$$\text{Emission} = \text{Activity}_{r,i} * \text{EF-base}_{r,i} * \text{AF}_{r,i} \quad (\text{Equation 1})$$

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;
- > 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 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).

Some generic rules are used in describing changes in emissions over time (see further). The abatement factor (AF) is determined in the climate policy model FAIR (see Component [Climate policy](#)). The emission factor approach has some limitations, the most important of which is capturing the consequences of specific emission control technology (or management action) for multiple gas species, either synergies or trade-offs.

#### 3) Gridded emission factor with spatial distribution (GEF)

GEF is a special case of the EF method, where a proxy distribution is used to present gridded emissions. This is done for a number of sources, such as emissions from livestock ([Emission table](#)).

#### 4) Gridded process model (GPM)

Land-use related emissions of  $\text{NH}_3$ ,  $\text{N}_2\text{O}$  and  $\text{NO}$  are calculated with grid-specific models (Figure

### Projects/Applications

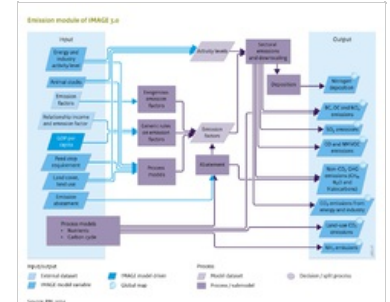
- > Roads from Rio+20 (2012) project

### Key publications

- > Braspenning Radu et al., submitted
- > Van Vuuren et al., 2006
- > Van Vuuren et al., 2011b

### References

[Expand]



Flowchart Emissions. See also the [Input/Output Table](#) on the introduction page. 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 ([Emission table](#)).

Flowchart). The models included in IMAGE are simple regression models that generate an emission factor (Figure Flowchart). For comparison with other models, IMAGE also includes the N<sub>2</sub>O 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.

### Emissions from energy production and use

Emission factors (Equation 1) are used for estimating emissions from the energy-related sources (Emission table). 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.

The emission factors for the historical period for the energy system and industrial processes are calibrated with the EDGAR emission model described by Braspenning Radu et al. (in preparation). 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<sub>2</sub> 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:

1. Cement and steel production. IMAGE-TIMER includes detailed demand models for these commodities (Component Energy supply and demand). Similar to those from energy use, emissions are calculated by multiplying the activity levels to exogenously set emission factors.
2. 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.
3. 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<sub>6</sub>). 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<sub>2</sub> exchanges between terrestrial ecosystems and the atmosphere computed by the LPJ model are described in [Carbon cycle and natural vegetation](#). The land-use emissions model focuses on emissions of other compounds, including greenhouse gases (CH<sub>4</sub>, N<sub>2</sub>O), ozone precursors (NO<sub>x</sub>, CO, NMVOC), acidifying compounds (SO<sub>2</sub>, NH<sub>3</sub>) and aerosols (SO<sub>2</sub>, NO<sub>3</sub>, BC, OC).

For many sources, the emission factor ([Equation 1](#)) is used ([Emission table](#)). 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<sub>4</sub> emissions from non-dairy and dairy cattle are calculated on the basis of energy requirement and feed type (see Component [Livestock systems](#)). High-quality feed, such as concentrates from feed crops, have a lower CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> 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<sub>2</sub>O 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<sub>2</sub>O 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-use related emissions of NH<sub>3</sub>, N<sub>2</sub>O and NO are calculated with grid-specific models. N<sub>2</sub>O 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<sub>3</sub> ([Bouwman et al., 1997](#)).

For N<sub>2</sub>O 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<sub>3</sub> 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<sub>2</sub>O methodology proposed by IPCC ([2006](#)). This methodology represents only anthropogenic emissions. For emissions from fertilizer fields this is the emission from a fertilized plot minus that from a control plot with zero fertilizer application. For this reason, soil emissions calculated with this methodology cannot be compared with the above model approaches, which yields total N<sub>2</sub>O 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<sub>4</sub> emissions from fossil fuel production and transport, N<sub>2</sub>O emissions from transport, CH<sub>4</sub> emissions from enteric fermentation and animal waste, and N<sub>2</sub>O emissions from animal waste according to the IPCC method. These abatement files are calculated in the IMAGE climate policy sub-model FAIR (Component [Climate policy](#)) by comparing the costs of non-CO<sub>2</sub> abatement in agriculture and other mitigation options.

### Parts of Emissions

1. [Introduction page](#)
2. **Model description**
3. [Policy issues](#)
4. [Data, uncertainty and limitations](#)

5. Overview of references

*Additional info*

6. Emission table

Category: ComponentDescription

[What links here](#) [Printable version](#) [Browse properties](#)







## Emissions/Policy issues

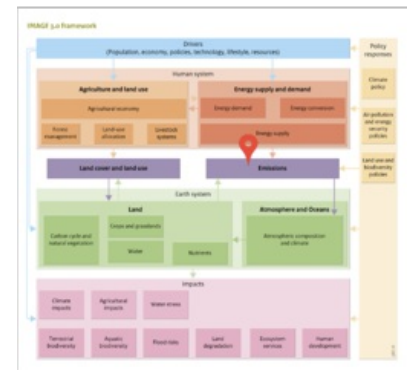
< Emissions

### Parts of Emissions

1. Introduction page
2. Model description
3. **Policy issues**
4. Data, uncertainty and limitations
5. Overview of references

### Contents [hide]

- 1 Baseline developments
- 2 Policy interventions
- 3 Effects of policy interventions on this component



### 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 the figure below 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.

### Projects/Applications

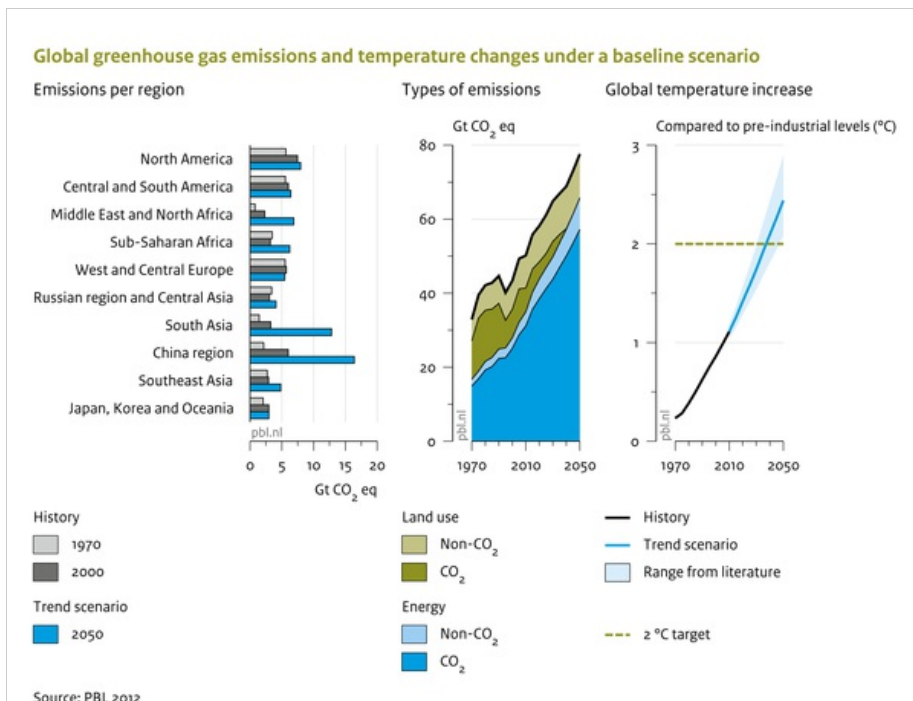
> [Roads from Rio+20 \(2012\) project](#)

### Key publications

- > [Braspenning Radu et al., submitted](#)
- > [Van Vuuren et al., 2006](#)
- > [Van Vuuren et al., 2011b](#)

### References

[\[Expand\]](#)



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.

### Policy interventions

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

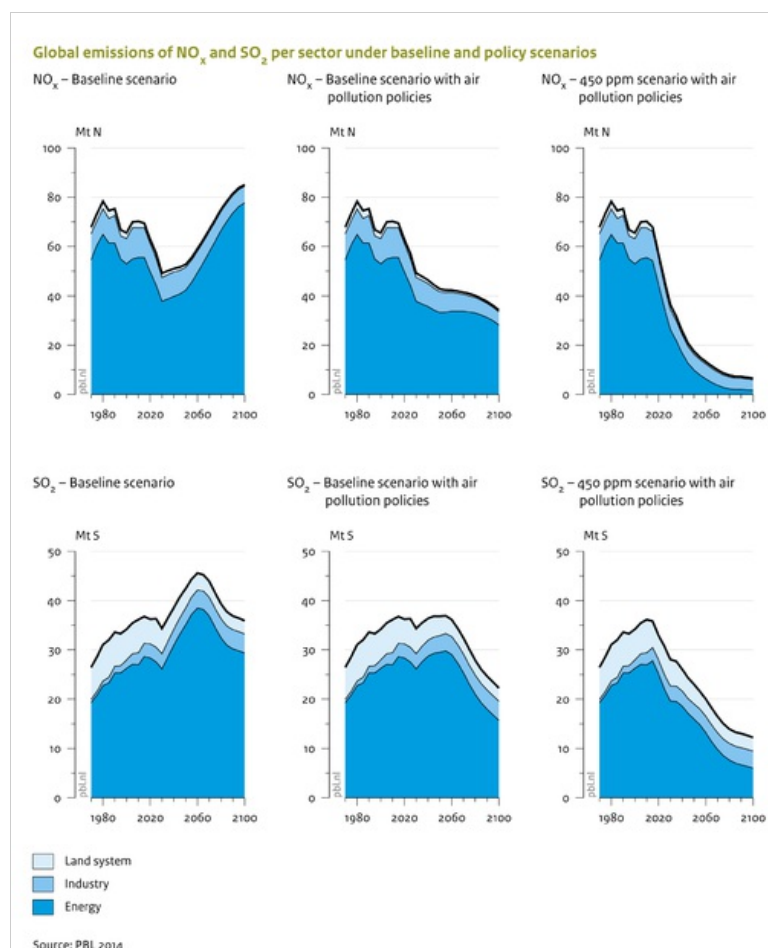
- > Introduction of climate policy, which leads to systemic changes in the energy system (less combustion) and thus, indirectly to reduced emissions of air pollutants ([Van Vuuren et al., 2006](#)).
- > Policy interventions can be mimicked by introducing an alternative formulation of emission factors 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., 2011b). By increasing the amount of feed crops in the cattle rations,  $CH_4$  emissions can be reduced. Production of crop types 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 the figure below. Where climate policy is particularly effective in reducing  $SO_2$  emissions, air pollution control policies are effective in reducing  $NO_x$  emissions.

See also the Policy interventions Table below.



Climate policy has important co-benefits for air pollution.

## Effects of policy interventions on this component

Policy intervention	Description	Effect
Apply emission and energy intensity standards	Apply emission intensity standards for e.g. cars ( $gCO_2/km$ ), power plants ( $gCO_2/kWh$ ) or appliances ( $kWh/hour$ ).	
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.	
Carbon tax	A tax on carbon leads to higher prices for carbon intensive fuels (such as fossil fuels), making low-carbon alternatives more attractive.	
Change market shares of fuel types	Exogenously set the market shares of certain fuel types. This can be done for specific analyses or scenarios to explore the broader implications of increasing the use of, for instance, biofuels, electricity or hydrogen and reflects the impact of fuel targets. (Reference: Van Ruijven et al., 2007)	
Change the use of electricity and hydrogen	It is possible to promote the use of electricity and hydrogen at the end-use level.	
Excluding certain	Certain energy technology options can be excluded in the model	

Policy intervention	Description	Effect
Implementation of biofuel targets	for environmental, societal, and/or security reasons. (Reference: <a href="#">Kruyt et al., 2009</a> ) Policies to enhance the use of biofuels, especially in the transport sector. In the Agricultural economy component only 'first generation' crops are taken into account. The policy is implemented as a budget-neutral policy from government perspective, e.g. a subsidy is implemented to achieve a certain share of biofuels in fuel production and an end-user tax is applied to counterfinance the implemented subsidy. (Reference: <a href="#">Banse et al., 2008</a> )	
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.	
Improving energy efficiency	Exogenously set improvement in efficiency. Such improvements can be introduced for the submodels that focus on particular technologies, for example, in transport, heavy industry and households submodels.	
REDD policies	The objective of REDD policies it to reduce land-use related emissions by protecting existing forests in the world; The implementation of REDD includes also costs of policies. (Reference: <a href="#">Overmars et al., 2012</a> )	Less emissions due to deforestation and land-use change

Parts of Emissions

- 1. Introduction page
- 2. Model description
- 3. Policy issues
- 4. Data, uncertainty and limitations
- 5. Overview of references

Category: ComponentPolicyIssue





## Emissions/Data uncertainties limitations

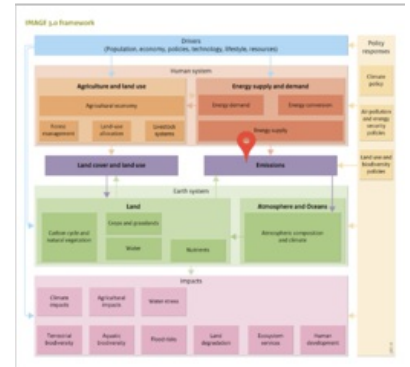
[< Emissions](#)

### Parts of Emissions

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

### Contents [\[hide\]](#)

- 1 Data, uncertainties and limitations
  - 1.1 Data
  - 1.2 Uncertainties
  - 1.3 Limitations



### 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 \(IPCC, 2006\)](#)

#### 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<sub>2</sub> are less uncertain than those for non-CO<sub>2</sub> 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 include emissions from peat and peat fires, although they constitute an important source of air pollutants and CO<sub>2</sub> emissions ([IPCC, 2007a](#)).

### Projects/Applications

- > [Roads from Rio+20 \(2012\) project](#)

### Key publications

- > [Braspenning Radu et al., submitted](#)
- > [Van Vuuren et al., 2006](#)
- > [Van Vuuren et al., 2011b](#)

### References

[\[Expand\]](#)

### Parts of Emissions

1. Introduction page
2. Model description
3. Policy issues
4. **Data, uncertainty and limitations**
5. Overview of references

Category: [ComponentDataUncertaintyAndLimitations](#)

[What links here](#) [Printable version](#) [Browse properties](#)





## Emissions/References

[< Emissions](#)

### Key publications

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O. Braspenning Radu, M. van den Berg, Z. Klimont, S. Deetman, G. Janssens-Maenhout, M. Muntean, F. Dentener, D.P. van Vuuren (). Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios. Submitted, available on request.

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Category: AllReferencesPages

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