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Modeling Land Use

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Abstract:

Agriculture is confronted to the following question: under what circumstances will humanity be able to feed its future population? The recent answers brought to this question – increase of surfaces and above all intensification of production – are showing their limits. And indeed, there is only a small margin left for the increase of both parameters. What is more, the environmental impacts produced threaten the system's sustainability. Among the environmental challenges that have to be faced, adaptation to climate changes originates major uncertainties.

The setting up of a tool for economic prospective including agronomic and technical constraints thus appears to be necessary. None of the existing models which are presented briefly in this report takes into account simultaneously economic processes, production mechanisms and environmental feedbacks.

We present in this report the questions raised by the representation of supply in Nexus-Land-Use, a partial equilibrium model which was designed to tackle these aspects. The rarity and the price of the available data are the main constraints to the development of such a model. Moreover, the question of the potential evolution of yields remains a major difficulty. Finally, taking into account the production process requires dealing with the question of the representation of technical itineraries, as well as that of spatial representation. The complex question of water is in this respect particularly important.

Besides, an example of a technicoeconomic representation is presented for the case of ruminant livestock breeding, for which a simplified production function is proposed. And finally, a simplified version of the model Nexus Land-Use for Europe-15 stresses the importance of the questions just mentioned.

Résumé :

L'agriculture est confrontée à la question suivante : sous quelles conditions sera-t-on capable de nourrir la population future ? Les réponses récentes – augmentation des surfaces et surtout intensification – commencent à montrer leurs limites. En effet, il ne reste que peu de marge d'augmentation de ces paramètres. En outre, les impacts environnementaux engendrés menacent déjà la durabilité du système. Parmi les défis environnementaux que l'agriculture doit relever, l'adaptation aux changements climatiques est à l'origine d'incertitudes majeures.

La mise au point d'un outil de prospective économique qui intègre les contraintes agronomiques et techniques apparaît donc nécessaire. Aucun des modèles existants, présentés ici dans une brève revue, ne prend en compte simultanément les processus économiques, les mécanismes de production et les rétroactions environnementales.

Nous présentons ici les questions soulevées par la représentation de l'offre dans Nexus land-use, modèle d'équilibre partiel, qui a été développé pour traité ces points. La rareté et le prix des données disponibles sont les principales contraintes au développement d'un tel modèle. En outre, la question de l'évolution potentielle des rendements demeure un point d'achoppement déterminant. Enfin, la prise en compte du processus de production nécessite de se poser la question de la représentation des itinéraires techniques, ainsi que celle de la représentation spatiale. Dans ce contexte, la question complexe de l'eau est particulièrement importante.,

Par ailleurs, un exemple de représentation technico-économique est présenté pour le cas de l'élevage des ruminants pour lequel une fonction de production simplifiée est proposée. Enfin, une version simplifiée du modèle Nexus land-use, pour l'Europe des 15, montre l'importance de ces questions.

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Introduction

This report deals with our work at the CIRED (International Centre for Research on Environment and Development). We did a 6 month-internship working together on the supply side of Nexus Land-Use, a technical and economic model of global land use developed by Gitz and Ollivier (2007). The underlying very general problematic of our work is a better understanding of the interface between agriculture and environment. This report first presents a bibliographic review of the long going effects of intensive agriculture on the environment, and the future challenges that agriculture will have to face as a consequence. We quickly remind the issues related to the global political context. Then we turn to a review of different land use models, and draw a few conclusions for Nexus Land Use itself. We move further to a highlight of the difficulties inherent to the use of databases. Then we deal with methods to improve certain aspects of the supply side of Nexus, such as the representation of yields, spatialization, taking into account water use for irrigation, integrating a new model for livestock production etc. The last part is devoted to the presentation of a simplified model, developed for the European Project MATISSE, and its results.

1. Consequences of living in a finite world: can we be productive and sustainable in the same time?

> The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race. The vices of mankind are active and able ministers of depopulation. They are the precursors in the great army of destruction, and often finish the dreadful work themselves. But should they fail in this war of extermination, sickly seasons, epidemics, pestilence, and plague advance in terrific array, and sweep off their thousands and tens of thousands. Should success be still incomplete, gigantic inevitable famine stalks in the rear, and with one mighty blow levels the population with the food of the world.
>
> *Thomas Robert Malthus 1766–1834*

1.1. The present Human domination of the Earth…

The growth of the human population, and growth in the resource base used by humanity, is sustained by a set of human activities such as agriculture, industry, fishing, and means of transportation. These activities have transformed the land surface through cropping, forestry, and urbanization. The pace, magnitude and spatial reach of human alterations of the Earth's land surface are unprecedented (Lambin et al. 2001). And indeed, human alteration of Earth is substantial and growing. Thus, between one-third and one-half of the land surface has been transformed by human action. Many ecosystems are dominated directly by humanity (agricultural fields, pastures, urban areas etc.), and no ecosystem on Earth's surface is free of indirect and pervasive human influence (Vitousek et al. 1997). Nearly 50% of the land surface potentially under vegetation has been affected by agriculture, in the form of croplands, pastures and rangelands. These numbers have large uncertainties, but they undoubtedly give an accurate image of the situation (Tilman et al. 2002, Nonhebel 2005). Agriculture profoundly affects global carbon, water and nutrient cycles (alteration of the major biogeochemical cycles), as well as planetary surface energy balance (Nonhebel 2005), and adds or removes species and genetically distinct populations in most of Earth's ecosystems (Vitousek et al. 1997).

Quantifying the impact of human activities on the earth system through land transformation is extremely difficult. Land transformation encompasses a wide variety of activities that vary substantially in their intensity and consequences (Tilman et al. 2002).

Remote sensing is a very useful technique, but only recently has there been a serious scientific effort to use high-resolution civilian satellite imagery to evaluate even the more visible forms of land transformation, such as deforestation, on continental to global scales. It shows that, on the one hand, up to 10 to 15% of Earth's land surface is occupied by row crop agriculture or by urban-industrial areas, and another 6 to 8% has been converted to pastureland (Tilman 1999). These systems are completely transformed by human activity. It means that about half of global usable lands (excluding desert, tundra, rock or boreal areas) are already under pastoral or intensive agriculture (Tilman et al. 2002).

On the other hand, every terrestrial ecosystem, even those that are not directly exploited by humanity, is affected by increased atmospheric carbon dioxide (CO_2), and most ecosystems have a history of hunting and other low-intensity resource extraction (Tilman 1999).

1.2. …in order to feed the population…

1.2.1. Agriculture enables the exponential increase of the world population.

It should not be forgotten that the benefits of agriculture have been immense. Before the apparition of agriculture, the hunter-lifestyle supported about 4 million people globally according to Cohen (1996). Today, in comparison, modern agriculture feeds more than 6 billion people.

The nutritional energy requirement of a human body is of about 10 MJ[1] per day. There is not much difference in energy intake between developed and developing countries (Nonhebel 2005). The new feeding needs have been fulfilled by practicing agriculture on ever bigger surfaces and with ever more intensive techniques. As a consequence of both extensification and intensification, agriculture was able to realize the incredible food production increase needed to feed the population: global cereal production has thus doubled over the past 40 years (Tilman et al. 2002).

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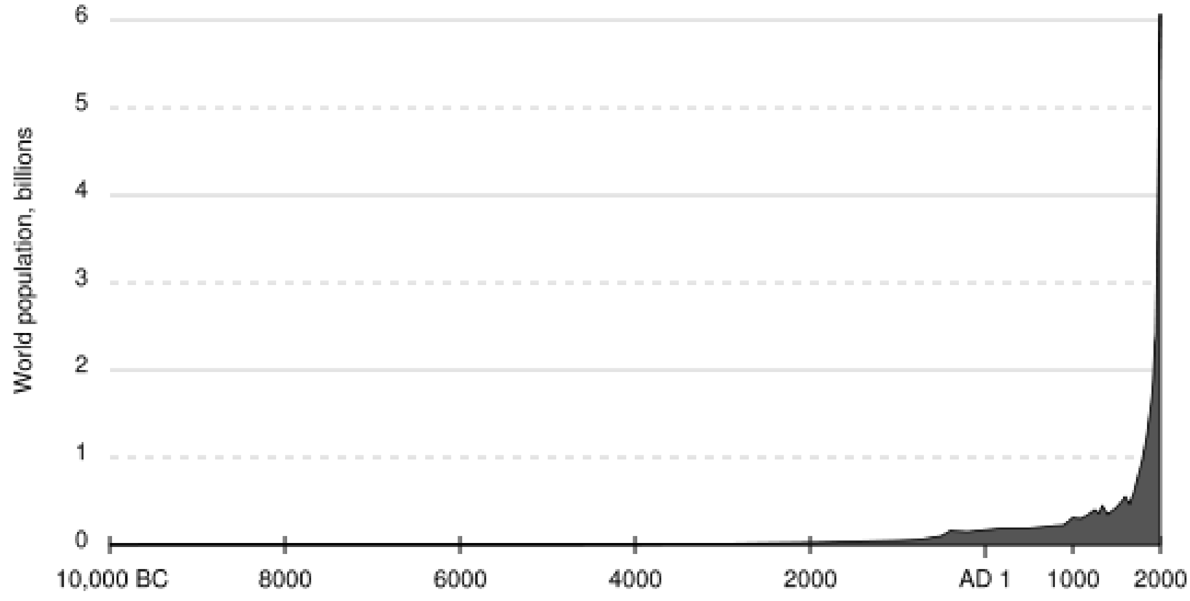
[1] Megajoule

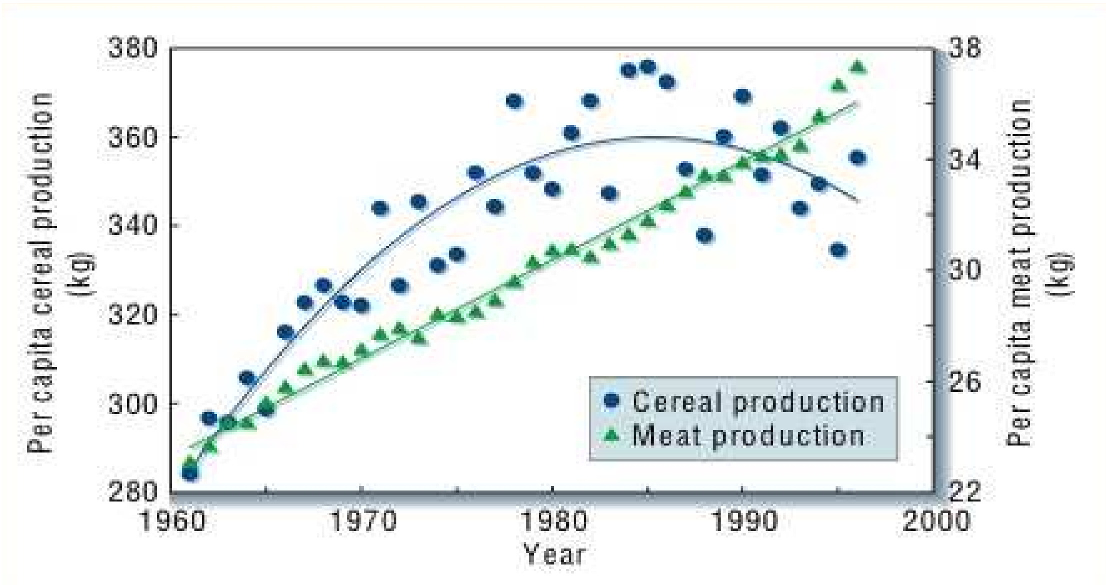
Figure 1. Evolution of world population (Cohen, 1996)



1.2.2. Not only there is more people, but they are richer

Wheat, Rice and Maize provide about two-thirds of all energy diets (Cassman 1999) and represent the foundation of human food supply. However, of course, the composition of the diet shows large differences between populations.

Figure 2. Long-term trends in average per capita food supply (Tilman et al. 2002)



The affluent consumption patterns are characterized by a high level of consumption of meat and other livestock products, supplemented by many “non-energetic” food items (coffee, tea, fruit juices, etc). This type of consumption is land intensive. During the past 40 years, global per capita meat production has increased by more than 60% (Tilman et al. 2002). For instance, in grain equivalent, a very basic menu of 200 kg of wheat per person can fulfill the yearly needs for food. In comparison, more affluent diets, composed of meat, etc. are estimated to require four times as much grain equivalents (Penning de Vries et al. 1995). The production of 1 kg of meat can require between 3 and 10 kg of grain (Figure 2), a trend driven by increasing global per capita incomes, but threatened by stagnant or declining per capita grain production.

1.2.3. Demand drives supply that drives land domination

People's responses to economic opportunities, which are not only economically driven but also influenced by institutional factors, provoke land-cover changes. And indeed, opportunities and constraints for new land uses are created by local as well as national market and policies, even though, in the end, the quantity and the wealth of a population drive land use decisions. What is more, global forces become the main determinants of land use changes, as they amplify or attenuate local factors, and they influence trade in food products as well (Lambin et al. 2001).

For instance, tropical deforestation is driven largely by changing economic opportunities which, as mentioned above, are linked to yet other social, political and infrastructural changes (ibid.).

The parallel exponential rise of the human population and increase of the per capita consumption of resources over the last three centuries have strongly modified the Earth's biosphere and atmosphere composition (Ramankutty and Foley 1998).

1.3. … is the consequence of important land use change …

The new feeding needs have been fulfilled by changes in agriculture and land use, more particularly by the extension of agricultural surfaces and intensification (Tilman et al. 2002). But the issue of the future changes in land use is now of particular interest.

To be able to say anything on actual and future land use, we need to understand past changes. They can be analysed as follows.

Land-cover changes are of two types (Meyer and Turner 1992):

- conversion from one category of land cover to another
- modification of condition within a category

Conversion is the better documented and more readily monitored of the two types of land cover change, but too great an emphasis on it obscures important forms of land-use modification. Global expansion of cultivated land (conversion) is accelerating, as is the intensification of the use of lands already cultivated (modification). Those land use changes are the simple consequence of a growing human population.

1.3.1. Land use conversion

Terrestrial biosphere has always provided resources such as food or fiber for the human population.

Ramankutty and Foley (1998) estimated that roughly 18 million km^2 of terrestrial surface would be under some kind of some cultivation in 2000. This is the size of South America.

What is really striking is the rapidity of the land use change. Indeed, the world total cultivated land is estimated to have increased by 446% from 1700 to 1980 (+12 million km^2) (Meyer and Turner 1992). Over the last three centuries, roughly 12 million km^2 of forests and woodlands have been cleared, grasslands and pastures have diminished by about 5.6 million km^2 and cropland areas have increased by 12 million km^2 (ibid.).

Ramankutty and Foley (1992) have reconstructed a spatially-explicit global data set of croplands from 1992 back to 1700, using a simple algorithm which links contemporary satellite data and historical cropland inventory data. Using this method, they estimate that a loss of 11.4 million km^2 of forest/woodland and 6.7 million km^2 of savannas, grasslands, and steppes has occurred from pre-agricultural times to nowadays. What is more, land use change accelerated around 1850, and since 1850, it is estimated that 6 million km^2 of forest and woodland and 4.7 million km^2 of savannas, grasslands, and steppes have been cleared. Finally, 1.5 million km^2 of cropland were abandoned in previously forested areas, and 0.6 million km^2 in areas previously occupied by savannas, grasslands and steppes, all of this having occurred since 1850.

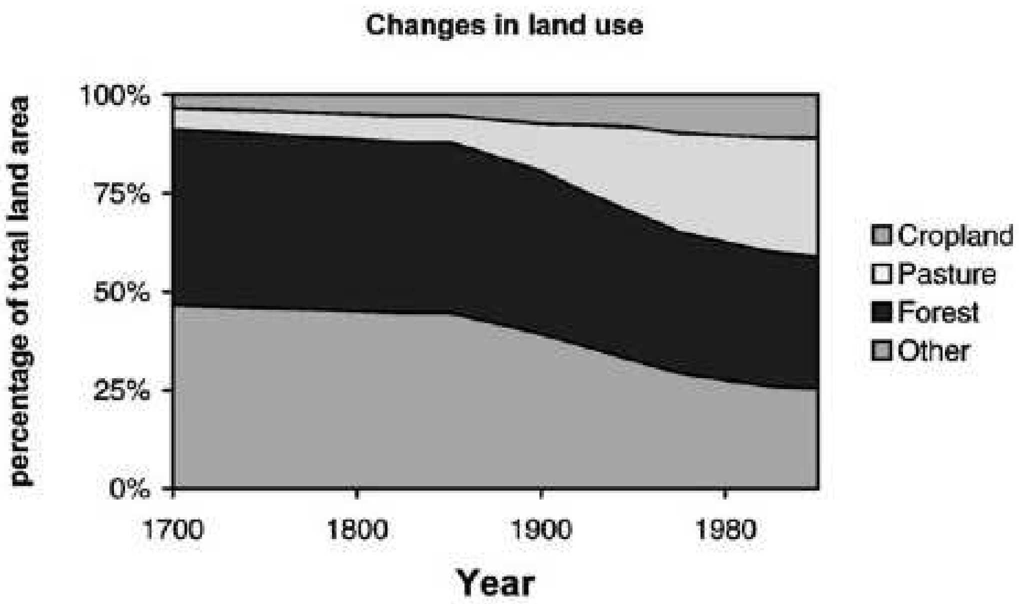


Figure 3. Estimated changes in land use from 1700 to 1995 (Lambin et al. 2001)

What is more, land use is changing quicker and quicker. Total cropland area has increased during the first half of the 20th century. The increase was the most rapid during the 1950s, when several cropland extension programs were initiated worldwide (Central Asia) (Bondeau et al. 2007). Only in the 1980s, it slowed down and reached quasi-stable conditions. From the 1980’s on, deforestation in the tropics has been largely compensated by afforestation in the temperate zones.

1.3.2. The fantastic production potential created by the “Green revolution”

But yields increase far more than surfaces. It is mainly the result of greater inputs of fertilizers, water and pesticides, new crop strains and other technologies of the “Green Revolution” (Tilman et al. 2002).

Grain harvest has doubled over the past 35 years, so it now exceeds 2 billion tons per year. Some of this increase can be attributed to a 12% increase in world cropland area, but most of these production gains result from “green revolution” technologies (Lambin et al. 2001, Tilman 1999, Foley et al. 2005).

Although appropriate government policies and social conditions also were required to promote intensification, three production factors were largely responsible for the increased production achieved by farmers. These factors were (Foley et al. 2005, Bondeau et al. 2007, Cassman 1999):

(i) new “miracle” varieties of wheat and rice released in the mid to late 1960s, which had a higher harvest index[2], shorter stature, and increased stalk strength that reduced susceptibility to lodging, as well as steady improvement in maize hybrids;

(ii) increased application of N fertilizer, which allowed greater net primary production without fear of lodging. The doubling of agricultural food production over the last 35 years was associated with a 6.87-fold increase in nitrogen fertilization, a 3.48-fold increase in phosphorus, fertilization, and a 1.68-fold increase in the amount of irrigated cropland. (Tilman 1999)

(iii) Massive investments in irrigation infrastructure, which were justified by the greater yield potential which it enabled; fertilizer responsiveness; and increased cropping intensity made possible with new variety and hybrids.

In addition, the reduction of the time separating planting to maturity for the new varieties also permitted an increase in cropping intensity. While only one crop harvested per year was possible with landrace genotypes, earlier maturity allowed two and sometimes three cereal crop harvests per year on the same piece of land.

The foundation of global food security now is built on four major cereal production systems in which modern farming practices are used. These systems include (Cassman 1999):

(i) Irrigated annual double and triple-cropping continuous rice systems in the tropical and subtropical lowlands of Asia (about 25% of global rice production),

(ii) Irrigated annual rice-wheat double-cropping system in northern India, Pakistan, Nepal and Southern China,

(iii) Temperate maize-based, rain-fed cropping systems of the North American plains (40% of the global maize supply),

(iv) The favorable rain-fed wheat systems of Northwest and Central Europe (20% of global wheat supply).

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[2] Harvest Index (HI): ratio of grain to total crop biomass

Increased yield from intensification of wheat, rice, and maize systems have contributed to 94-96% of the total increase in the global supply of wheat, rice and maize since 1967. An additional 446 million ha of land would be required to achieve 1997 levels of wheat, rice and maize production at the 1967 yield levels.

The moving-average peak at 371 kg per capita cereal production was reached in 1984 and fell to around 350 kg in the mid-1990s. Since 1983 the world's population has been growing faster than cereal production (Dyson 1998).

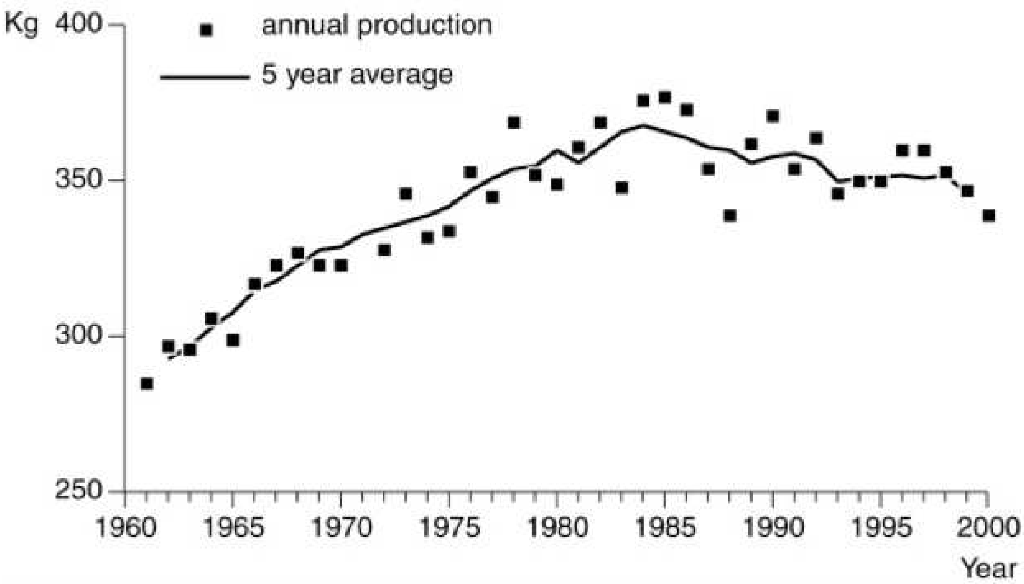


Figure 4. World per capita cereal production, 1961-2000 (Dyson 1998)

A few authors (Dyson 1998) have used statistical models to argue that this slow down is due to changing policies rather than a technical deficiency. They show that the world cereal yields follow a more or less linear or "arithmetical" (to use Malthus' term) trend. Of course, on a rising base this linear trend translates into a declining percentage increase.

Other authors (Cassman 1999) have a more technical point of view. They argue that meeting future food demand while minimizing expansion of cultivated area primarily will depend on continued intensification of the four systems previously mentioned. However, the way in which further intensification will have to be achieved will differ markedly from the past, because the exploitable gap between average farm yields and genetic yield potential is closing. At present, the rate of increase in yield potential is much smaller than the expected increase in demand. Hence, average farm yields must reach 70 to 80% of the yield potential ceiling within 30 years in each of these major cereal systems to meet the population needs.

Although land-use practices vary greatly across the world, their ultimate outcome is generally the same: the acquisition of natural resources for immediate human needs. It often happens at the expense of degrading environmental conditions. Current trends of land use allow humans to appropriate an ever-larger fraction of the biosphere goods and services, while simultaneously diminishing the capacity of global ecosystems to sustain food production, maintain freshwater and forest resources, and regulate climate and air quality (Foley et al. 2005).

Achieving consistent production at high levels without causing environmental damage will thus require improvements in soil quality and precise management of all production factors in time and space (Cassman 1999).

1.4. … and the cause of serious environmental issues

> If our children are hungry, we will cut every last tree. And we will not worry about the spotted owls, except maybe to eat them.
> *Ross Perot, American presidential candidate, 1930-….*

Although intensification has spared natural ecosystems from conversion to agricultural uses, greater use of applied inputs and inefficient farming practices has contributed to non-point-source pollution problems (Cassman 1999). Thus, at a global scale, land-use changes are cumulatively transforming land cover at an accelerating pace (Lambin et al. 1999, Lambin et al. 2001).

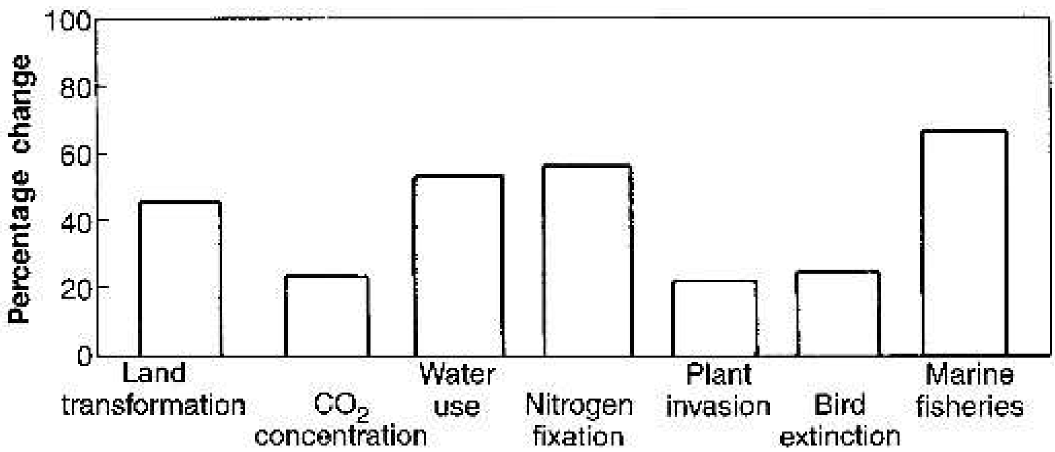


Figure 5. Human dominance or alteration of several major components of the Earth system (Vitousek et al. 1997)

Yet, environmental issues form a confusing and often illogical collection that is difficult to classify. They can be regarded as global, regional or local, of which the only truly global issues result from alterations of the atmosphere or the ocean. They directly impact biotic diversity worldwide; contribute to local and regional climate change as well as to global climate warming; they are the primary source of soil degradation; and by altering ecosystem services, they affect human needs. Such changes also determine, in part, the vulnerability of places and people to climatic, economic or socio-political perturbation (Lambin et al. 2001).

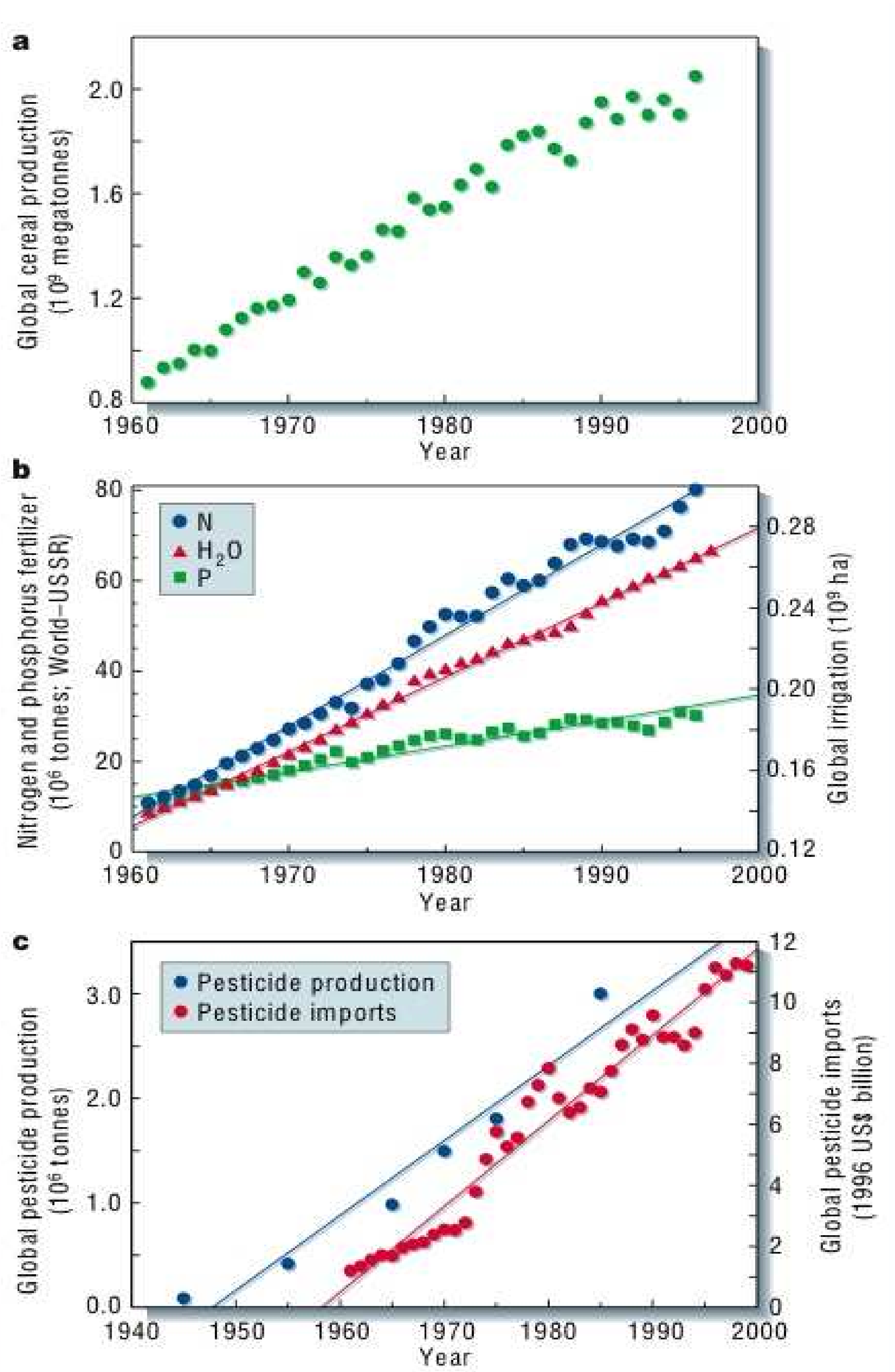


Figure 6. Agricultural trends over the past 40 years (Tilman et al. 2002)

However, some very important issues are local in origin, but occur so frequently that they are considered to be global. Because of its global spread, agriculture is concerned with most of such issues. These effects have occurred so widely in intensive developed agriculture, that intensive agriculture is now often regarded as damaging to the environment on a global scale (Tinker 1997, Lambin et al. 2001).

At this point, it seems interesting to distinguish between two ways land use change provokes the alteration of the land surface and its biotic cover (Meyer and Turner 1992, Lambin et al. 1999):

- By affecting a globally fluid system (atmosphere, world climate, sea level), for instance through methane (CH_4) accumulation. There is an increased concern about human-induced impacts on the biogeochemical foundation of the biosphere and their implications for climate change.
- By occurring in a localized or patchwork fashion in enough places to sum up to a globally (or regionally) significant total. For instance, cumulative land cover degradation designates problems such as global biodiversity loss, which are not too serious at a local scale, but can become of great importance with the accumulation of occurrences throughout the world. On the other hand, patchwork land cover degradations are very serious at a local scale, but their accumulation does not add up seriousness until a certain threshold. Examples of the latter degradations are regional irreversible consequences in critical regions and vulnerable places where soil degradation or hydrological changes happen.

1.4.1. Chemical cycles

Between 1960 and 1995, global use of nitrogen fertilizer increased sevenfold and phosphorus use increased 3.5-fold (Tilman et al. 2002) (figure 6). Both are expected to increase another threefold by 2050, unless there is a substantial increase in fertilizer efficiency. Agriculture has become the largest source of excess nitrogen and phosphorus to waterways and coastal zones (Foley et al. 2005). Indeed, fertilizer use and legume crops have almost doubled total annual nitrogen inputs to global terrestrial ecosystems. Similarly, phosphorus fertilizers have contributed to a doubling of annual terrestrial phosphorus mobilization globally. All other things being equal, the highest efficiency of nitrogen fertilizer is achieved with the first increments of added nitrogen. Efficiency declines at higher levels of addition. Consequently, nowadays, only 30–50% of applied nitrogen fertilizer and about 45% of phosphorus fertilizer is taken up by crops.

Such non-point nutrient losses harm off-site ecosystems, water quality and aquatic ecosystems, and contribute to changes in atmospheric composition. For instance, nitrogen loading to estuaries and coastal waters, and phosphorus loading to lakes, rivers and streams, are responsible for over-enrichment, eutrophication and low-oxygen conditions that endanger fisheries.

Nitrogen may be the biggest problem. Nitrogen (N) is unique among the major elements required for life, in that its cycle includes a vast atmospheric reservoir (N_2) that must be fixed (combined with carbon, hydrogen, or oxygen) before it can be used by most organisms. Human activity has substantially altered the global cycle of N by fixing N deliberately for fertilizer production, and inadvertently during fossil fuel combustion (Vitousek et al. 1997). Industrial fixation of N fertilizer increased from under 10 Tg per year in 1950 to 80 Tg per year in 1990. It is expected to increase to over 135 Tg per year by 2030 (Vitousek et al. 1997). Cultivation of soybeans, alfalfa, and other legume crops that fix N symbiotically, enhances fixation by another 40 Tg per year. Thus, overall, human activity adds at least as much fixed N to terrestrial ecosystems as do all natural sources combined.

Alteration of the N cycle has multiple consequences. In the atmosphere, these include:

- An increasing concentration of the greenhouse gas nitrous oxide globally;
- Substantial increases in fluxes of reactive N gases (two-thirds or more of both nitric oxide and ammonia emissions globally are human-caused)
- A substantial contribution to acid rain and to the photochemical smog

1.4.2. The importance of water in economic and environmental studies

Globally, humanity now uses more than half of the runoff water that is fresh and reasonably accessible, with about 70% of this use in agriculture (Vitousek et al. 1997). Global water withdrawals now total about 3900 km^3 per year, that is, nearly 10% of the total global renewable resource. The consumptive use of water (that is, water which is not returned to the watershed) is estimated to be between 1800 and 2300 km^3 per year. Agriculture alone accounts for about 85% of global consumptive use (Foley et al. 2005).

Agricultural water demand refers to four different types of uses: irrigation water, water used for livestock, water used in forestry and aquaculture. The two latter ones are in general negligible and are not dealt with in considerations about agricultural water use (Water Strategy Man).

In developing countries, irrigated land accounts for only 20% of the arable area. But due to higher yields and more frequent harvests, it supplies 40% of the crop production and close to 60% of the cereal production. On the other hand, irrigated agriculture is by far the most important water user in the world: it is responsible for over 70 % of all water withdrawn for human use (Heistermann, 2006).

Yet water is regionally scarce, and as much as 6% of Earth's river runoff is evaporated as a consequence of human manipulations. Major rivers, including the Colorado, the Nile, and the Ganges, are used so extensively that little water reaches the sea. Massive inland water bodies, including the Aral Sea and Lake Chad, have been greatly reduced in extent by water diversions for agriculture (Vitousek et al. 1997).

Thus, growing demand for water, uncertainties in natural water supply and new requirements imposed by environmental legislation are posing serious challenges at maintaining water quality and meeting demand for water resources (Heistermann et al., 2006a). In this context, taking into account water seems to be an important aspect to study in land use modelling. Water is important in considerations about land use from at least two perspectives:

(1) water scarcity can limit crop yields, and on the other hand, water availability can considerably improve yields through irrigation practices, thus water availability is a constraint for the allocation of land use

(2) water quantity and quality are affected by (among other things) agricultural practices, for agricultural input such as nitrates and phosphates are washed off the land into rivers, and agriculture draws on water resource through irrigation practices etc.

Water for livestock can be considered roughly as a function of the number of animals of each kind and age class.

Irrigation is a more complicated subject because there needs to be consideration about geography. Irrigation has contributed heavily to the increase in agricultural productivity in the past. Indeed, irrigated lands account for a substantial portion of the increased yields obtained during the Green Revolution. However, the global rate of increase in irrigated area is declining. Indeed, per capita irrigated area has declined by 5% since 1978, and new dam constructions may allow only a 10% increase in water for irrigation over the next 30 years (Tilman et al. 2002). What is more, expansion of irrigation systems is limited by environmental and health related effects, such as soil salinization and the spread of water borne diseases. The major factors contributing to these irrigation problems are: unpriced water resources and heavily subsidized water use, inadequate planning, construction and maintenance of water systems, unassigned water rights or rules that limit the transfer of rights, conflicts with development and urban planning goals (Reilly and Schimmelpfennig 1994). Unless water-use efficiency is increased, greater agricultural production will require increased irrigation. For example, technology such as drip ad pivot irrigation can improve water-use efficiency and decrease salinization.

1.4.3. Impacts on albedo and greenhouse gas emissions

The potential interaction between climate change and agriculture may be important and complicated. In the context of global climatic change, and with concern for food security, scientific communities of different disciplines need to cooperate more efficiently than ever, and in an integrated fashion, to make sure any food crisis has been overcome before any climate change crisis develops.

Land use is a driving force in the gas emissions and plays an important role in global warming. According to the Intergovernmental Panel on Climate Change (IPCC), the three main causes of the increase in greenhouse gases observed over the past 250 years have been fossil fuels, land use, and agriculture. It is estimated that since 1850, roughly 35% of the CO_2 equivalent emissions resulted directly from land use and agriculture (Foley et al. 2005). Nowadays, land use is still a very significant contributor to CO_2 emissions.

Agriculture itself contributes to greenhouse gas increases through land use in four main ways:

- CO_2 releases provoked by deforestation. Indeed, the currently accepted carbon balance assessed for the earth includes a loss of 2 Gt Carbon per annum from forest removal (Tinker 1997).
- Methane releases from rice cultivation, which are said to produce 12% of the global methane (Tinker 1997)
- Methane releases, from enteric fermentation in cattle
- Nitrous oxide releases, from fertilizer application

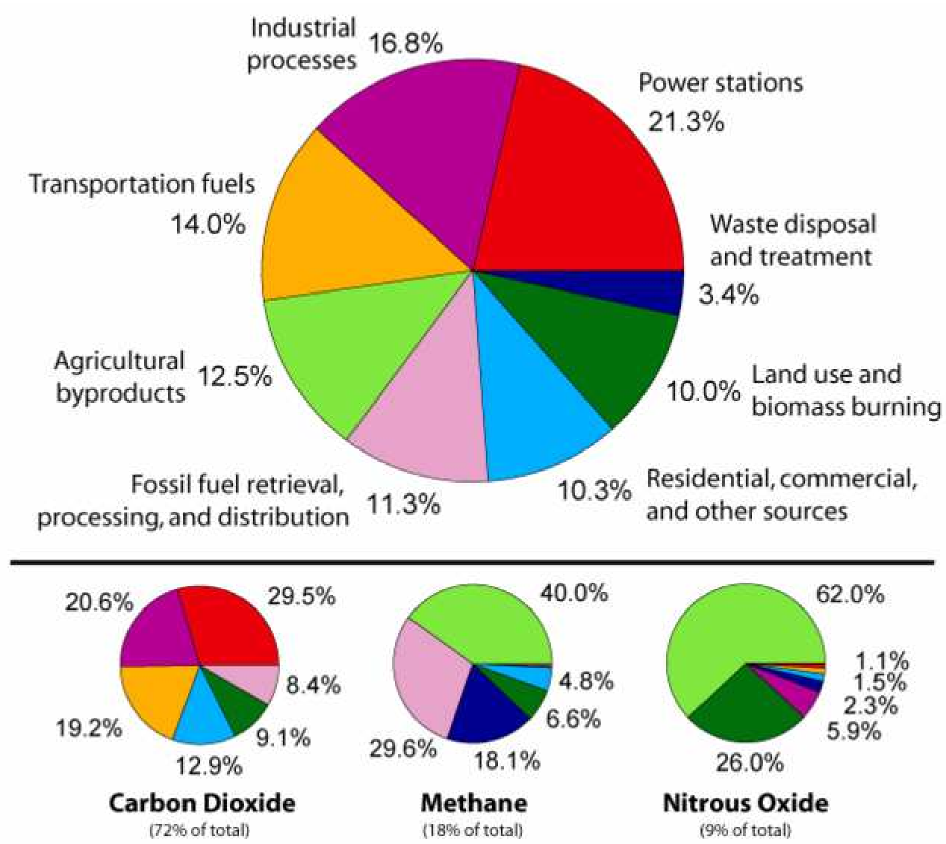
Together, these agricultural processes comprise 54% of methane emissions, roughly 80% of nitrous oxide emissions, and virtually all carbon dioxide emissions tied to land use (IPCC).

The planet's major changes to land cover since 1750 have resulted from deforestation in temperate regions. When forests and woodlands are cleared to make room for fields and pastures, the albedo of the affected areas increases. This can result in either warming or cooling effects, depending on local conditions. Deforestation also affects regional carbon reuptake, which can result in increased concentrations of CO_2, the dominant greenhouse gas. Land-clearing methods such as slash and burn compound these effects by burning biomatter, which directly releases greenhouse gases and particulate matter, such as soot, into the air.

Livestock and livestock-related activities such as deforestation and increasingly fuel-intensive farming practices are responsible for over 18% of human-made greenhouse gas emissions, including:

- 9% of global carbon dioxide emissions
- 35 to 40% of global methane emissions (chiefly due to enteric fermentation and manure)
- 64% of global nitrous oxide emissions (chiefly due to fertilizer use)

Figure 7. Annual Greenhouse Gas Emissions by Sector (by R. Rohde, data from Emission Database for Global Atmospheric Research version 3.2, fast track 2000 project)



Livestock activities also contribute directly and disproportionately to land-use effects, since crops such as corn and alfalfa are cultivated in order to feed the animals. It should not be forgotten that, worldwide, livestock production occupies 70% of all land used for agriculture, or 30% of the land surface of the Earth.

Spatially explicit global parameterizations of land used for agriculture have been produced for the estimation of biophysical and biochemical features such as land surface albedo, energy balance, roughness, greenhouse gas emissions, crop yields and carbon stocks. Differences in albedo and surface roughness between natural and cultivated vegetation have then been linked to atmospheric circulation, temperature and rainfall in coupled vegetation-climate modeling experiments.

This enabled the following estimations: a 24% (respectively 10%) reduction in global vegetation (respectively soil) carbon due to agriculture, and a 6 to 9 Pg Carbon of yearly harvested biomass in the 1990s (Bondeau et al. 2007).

Unfortunately, there is no appropriate global data set for soil carbon content of agricultural soils. Different data sets refer to different soil depths. What is more, past and present farming practices (such as tillage, residue management, crop rotation, etc.) play an important role in soil carbon content. However, it is generally accepted that carbon pools (vegetation, soil) are considerably lower under cultivation, except for dry conditions.

Land transformation can affect climate directly at local and even regional scales. It contributes to about 20% of current anthropogenic CO_2 emissions, and more substantially to the increasing concentrations of the greenhouse gases methane and nitrous oxide. Fires associated with land transformation alter the reactive chemistry of the troposphere, bringing elevated carbon monoxide concentrations to the air (Vitousek et al. 1997).

We will now focus briefly on carbon. Life on Earth is indeed based on carbon, and the CO_2 in the atmosphere is the primary resource for photosynthesis. Humanity adds CO_2 to the atmosphere by mining and burning fossil fuels (residue of life from the distant past), and by converting forests and grasslands to agricultural and other low-biomass ecosystems. The net result of both activities is that organic carbon from rocks, organisms, and soils is released into the atmosphere as CO_2.

The growth of most plants is enhanced by elevated CO_2, but to very different extents. The tissue chemistry of plants that respond to CO_2 is altered in ways that decrease food quality for animals and microbes; and the water use efficiency of plants and ecosystems generally is increased. The fact that increased CO_2 affects species differentially means that it is likely to drive substantial changes in the species composition and dynamics of all terrestrial ecosystems.

1.4.4. Impact on the biotope

Land transformation represents the primary driving force in the loss of biological diversity worldwide (Vitousek et al. 1997).

Human modification of Earth's biological resources (its species and genetically distinct populations) is substantial and growing. Extinction is a natural process, but the current rate of loss of genetic variability, of populations, and of species is far above background rates. Recent calculations suggest that rates of species extinction are now 100 to 1000 times those before humanity's dominance of Earth and land transformation is estimated to be the single most important cause of extinction. 12% of mammals and 11% of birds are considered to be threatened, mainly by habitat destruction. Loss of habitat accounts for 36% of extinctions. The other main causes are hunting (23%) and introduction of new species (39%) (World Conservation and Monitoring Centre, 1992).

The current rates of land transformation eventually will drive many more species to extinction, although with a time lag that masks the true dimensions of the crisis. Moreover, the effects of other components of global environmental change (altered carbon and nitrogen cycles, and anthropogenic climate change) are just beginning and affecting land cover as well. This will undoubtedly be responsible for increasingly more extinctions.

Loss by land transformation of locally adapted populations within species, and of genetic material within populations, is a human-caused change that reduces the resilience of species and ecosystems while precluding human use of the library of natural products and genetic material that they represent.

Moreover, many ecologists argue that the stability or productivity of ecosystems is maintained by high biodiversity. However, some very productive and stable ecosystems have low diversity, e.g. coniferous forests, and the question is not yet settled.

Other arguments for conserving biodiversity are the possibility of obtaining valuable products of genes from hitherto unused organisms, and the ethical belief that we should not render any organism extinct (Tinker 1997).

1.4.5. Deforestation/desertification

Only a fraction of the world's land is suitable for agriculture and only a fraction of this is still unused. Much of the best of this potentially available land is at present under forest, and there is growing alarm about the rate of forest loss (Tinker 1997).

There are underlying conflicts over what any remaining "unused" land should be used for. Ecologists are insisting that forests must be maintained for biodiversity conservation. Energy and global change scientists want existing agricultural land to be turned over to forest, for carbon sequestration or biomass production. Meanwhile, the agricultural community is calculating how much extra land is needed to ensure food security. IMAGE output suggests considerable losses of African forest in the next century for this purpose.

Researchers were able to reconstruct pre-agriculture land cover and use it to estimate that an original 62 million km^2 of forest and woodland has been reduced by 9 million km^2, of which 7 million km^2 (that is, 15% of total forest and woodland) represent loss of closed forest. The loss in the developing tropics is estimated to contribute to an annual net global loss of 0.1 to 0.2 million km^2 of forest (Meyer and Turner 1992).

Forest disappears mainly for cultivation but also for ranching and pasture (South America), timber extraction (South Asia), fuelwood extraction (Africa, Indian Subcontinent), pollution (North America, Western Europe) (ibid.).

Reforestation and afforestation can result naturally from land abandonment or can be undertaken deliberately by state or private action (Meyer and Turner 1992).

The UNCOD[3] report of 1977 identifies 6% of the world's area as "man-made deserts", and close to a quarter of the world's surface as threatened by desertification. The 1984 UNEP[4] assessment estimated the annual degradation of land "to desert-like conditions" to be about 60,000 km^2, and the area annually "reduced to zero or negative net economic productivity" as more than 200,000 km^2. Desertification is principally associated with excessive pressure on grasslands.

Land use activities, primarily agricultural expansion and timber extraction, have caused a net loss of 7 to 11 million km^2 of forest in the past 300 years. Many land-use practices (forest grazing, road expansion, fuel-wood collection) can degrade forest ecosystem conditions (in terms of productivity, biomass, stand structure, and species composition) even without changing forest area (Foley et al. 2005).

[3] United Nations Conference on Desertification
[4] United Nations Environment Program

However, in many parts of the world, especially in East Asian countries, reforestation and afforestation are increasing the area of forested lands. Furthermore, forest management in many regions is acting to improve forest conditions. For example, inadvertent nitrogen fertilization, peatland drainage, and direct management efforts, increased the standing biomass of European forests by about 40% between 1950 and 1990, while their area remained largely unchanged. These forests have become a substantial sink of atmospheric carbon (0.14 Pg Carbon per year in the 1990s) (Foley et al. 2005).

1.4.6. Regional climate change

Land conversion can alter regional climates through its effects on net radiation, the division of energy into sensible and latent heat and the partitioning of precipitation into soil water, evapotranspiration and runoff (Foley et al. 2005).

Indeed, some scientists use numerical models simulating atmosphere and biosphere, in order to assess for example the effects of Amazon deforestation on the regional and global climate (Shukla et al. 1990). It was found that deforestation will lead to an important regional change, with a significant increase in surface temperatures and decrease in evapotranspiration and precipitation. The main consequences will be the quasi impossibility for the tropical forest to reestablish. Although large scale clearing of tropical forests may create a warmer and drier regional climate, clearing temperate and boreal forest is generally thought on the other hand to cool the climate, primarily through increased albedo (Foley et al. 2005).

So the global vegetation is not only determined by the local climate, but the global vegetation will influence the regional climate. This is due to changes in relative albedo, lower surface roughness length, higher stomatal resistance, shallower and sparser root systems, and lower availability storage capacity for soil moisture.

Alterations to the hydrological cycle can also affect regional climate (Vitousek et al. 1997). And indeed, irrigation increases atmospheric humidity in semi-arid areas, often increasing precipitation and thunderstorm frequency. Simulations suggest that the net effect of this transformation is to increase temperature and decrease precipitations regionally. Both estimates are however controversial.

1.4.7. Soils

The FAO estimates that 5.44 million km^2 of rainfed cultivated land have been lost worldwide to degradation. Another study estimates that 20 million km^2 of former crop land have been irreversibly lost due to degrading uses and to permanent cover land (Meyer and Turner 1992).

Some irrigated lands have become heavily salinized, causing a worldwide loss of about 1.5 million hectares of arable land per year, along with an estimated $11 billion in lost production. Up to 40% of global croplands may also be experiencing some degree of soil erosion, reduced fertility, or overgrazing (Foley et al. 2005).

2. Agriculture will need to face new challenges

2.1. To feed tomorrow's population

Although large surpluses of various food items exist on different world markets, this does not mean that there is a surplus of food at the global scale. The surpluses are rather due to incorrect distribution of food. There are estimations that 800 millions people worldwide suffer from malnutrition (WHO[5]).

Increases in food production are needed to respond to increases of the world population on the one hand, but also to respond to the increased consumption of luxury food items like meat, sweets and beverage by this population.

More precisely, a doubling of global food demand is projected for the next 50 years (Tilman et al. 2002). This doubling will have to result from a projected 2.4-fold increase in per capita real income and from dietary shifts towards a higher proportion of meat (much of it being grain fed) associated with higher incomes (Cassman 1997). What is more, most population projections show population following a logistic growth path toward eventual stabilization. For instance, UN current population projection (Harris and Kennedy 1999) foresees a population of 9 to 10 billion people in 2050 (of which 8 billion will be in currently developing nations). The Population Reference Bureau on the other hand expects the population to range from 7.7 to 11.2 billion people (Cassman 1999).

Further increases in agricultural output are thus essential for global political and social stability and equity. Doubling food production and sustaining food production at this level are major challenges. Doing so in ways that do not compromise environmental integrity and public health is a greater challenge still.

There is a general consensus that agriculture has the capability to meet the food needs of 8 to 10 billion people while substantially decreasing the proportion of the hungry population (Cassman 1999). If the Malthusian precipice is to be avoided, agriculture has to become more productive per unit area or it has to use larger areas of land. The latter is often difficult or impossible (Tinker 1997).

2.2. To adapt to climate change

Annual global temperatures have increased by about 0.4°C since 1980, with even larger changes observed in several regions. The effects of past changes remain unclear. It is likely that warming has improved yields in some areas, reduced them in others and had negligible impacts in still others. The relative balance of these effects at the global scale is unknown (Lobell and Field 2007).

[5] World Health Organization, http://www.who.int/

Various studies found that yields for principal crops have substantially increased since 1961, while temperatures and precipitations, spatially weighted for each crop, also exhibited several remarkable trends (ibid.). The impacts of these climatic trends on yields have been investigated by developing new empirical (or statistical) models of global yield response to climate. For instance, spatialised data was used to link yields, temperatures and water by Leff et al. (2004). The findings of such manipulations are that at least 29% of the variance in year-to-year yield changes was explained by the predictors (temperatures, precipitations) for all crops. The impact was particularly strong on wheat, maize and barley. The foregone production due to climate trends is of 19 million tons per year for wheat, 12 million tons per year for maize and 8 million tons per year for barley (which correspond respectively to $2.6 billion, $1.2 billion, and $1 billion). The results suggest that recent climate trends have had a discernible negative impact on global production of several major crops.

However, the impacts of global warming are likely to have been offset to some extent by fertilization effects of increased CO_2 levels, although the magnitude of these effects are uncertain and the subject of much debate (Lobell and Field 2007).

2.3. To provide solutions to live without fossil fuels

The issues at stake in studying the alternatives to fossil fuels are firstly the need for mitigation of the enhanced greenhouse effect. Secondly, there is a need to find new energetic solutions to be able to compensate diminishing and finite stocks of fossil fuels.

Global fossil energy is estimated to be 400 EJ[6] per year, that is, 0.01% of the annual incoming solar radiation (3.5 million EJ). To be used, incoming solar radiation needs to be converted. Photovoltaic cells convert solar energy in electricity but the efficiencies of this type of conversion are low, expensive, and the electricity produced is difficult to stock (Nonhebel 2005).

Another option to exploit solar radiation is the use of plant material (biomass, wood). Plants indeed convert naturally photons in organic material (glucose), by photosynthesis. This source of energy was used before the industrial revolution in the form of the burning of fuelwood for heating and cooking. In the modern context, to face climate change and finitude of fossil fuel stocks, biomass as energy source for modern societies has been put into the footlights again.

In developing countries biomass (wood) is still an important source of energy (38% of the total energy supply), while in industrialized world it only accounts for 3% of the energy supply.

The most frequently mentioned ways of exploiting this resource are: conversion into a transport fuel (biodiesel or ethanol) or into electricity. These conversion processes are not free of costs and require energy themselves. For example, the costs for wood chips as feedstock for electricity plants are estimated at 0.06 Euro per KWh, while feedstock for coal is 0.02 Euro per KWh (excluding taxes).

[6] Exajoule (10^{18} Joules)

The highest solar energy efficiency is obtained when high-input systems are used (heavy machinery, use of fertilizers and pesticides). This can be realized on high-quality soils, which are comparable to soils required for food production.

But about 1/3 of the globe is land (that is, 13 Gha), and there is only 1.5 Gha of arable land, 3.5 Gha of pasture and 4 Gha of forests and woodland. What is more, the need for food puts an extra limitation on the potentials for the use of solar radiation for energy.

Based on this observation, there are two points of view prevailing about the issue of biomass as a source of energy. The pessimistic viewpoint is that there is not enough land to fulfill the needs for food and energy when biomass is used as an energy source. According to the optimistic view, there is enough space but a lot of change is needed in the management of woodland and forest into intensive energy crop plantations.

To illustrate the importance of this topic in the current public debate, we can mention the European directive 2003/30/CE for the "promotion of biofuels". It indeed expects to reach an incorporation rate of 5.75% in the fossil fuels by 2010. But the energetic yield is not very good (between 1.19 for wheat ethanol and 2.5 for EMHV[7]), according to the systemic method used by INRA[8], and the cost is high. What is more, large surfaces are required (Sourie et al. 2005).

It is worth mentioning that the use of plant material as energy source leads to CO_2 emissions. This CO_2 however has been taken up from the atmosphere and incorporated in the structural plant material of the preceding growing season(s). The net emission of CO_2 from this energy source is therefore zero. Substitution of fossil fuels with energy from biomass should therefore lead to a reduction of CO_2 emissions.

2.4. To face important environmental issues

The main environmental impacts of agriculture come from the conversion of natural ecosystems to agriculture; from agricultural nutrients which pollute aquatic and terrestrial habitats and groundwater; and from pesticides. The impacts are worsened by the accumulation and the persistence of organic agricultural pollutants (Tilman et al. 2002).

Agricultural nutrients enter other ecosystems and modify them, through leaching, volatilization and the waste streams of livestock and humans. Pesticides can harm human health, as can pathogens, including antibiotic-resistant pathogens associated with certain animal production practices (ibid.).

The question that we address, with regard to all the issues we have raised up to now, is whether land use activities are degrading the global environment in ways that may ultimately undermine ecosystem services, human welfare, and the long term sustainability of human societies (Foley et al. 2005).

[7] Ester Méthylique d'Huile Végétale, or methylic ester of vegetable oil, also called diester or biodiesel
[8] Institut National de la Recherche Agronomique

3. Agriculture’s political context

3.1. Trade liberalization

Trade liberalization mechanisms are initiated by the World Trade Organization (WTO) negotiations. The WTO indeed conducts negotiations with all member parties through what is called rounds. For instance, the Doha Development Round commenced at Doha, Qatar in November 2001 and is still continuing. Its objective is to lower trade barriers around the world, permitting free trade between countries of varying prosperity. The Doha Round began with a ministerial-level meeting in Doha, Qatar in 2001. Subsequent ministerial meetings took place in Cancún, Mexico (2003), and Hong Kong, China (2005). Related negotiations took place in Geneva, Switzerland; Paris, France; and again in Geneva. Trade liberalization is thus a slow and complicated process.

As Svedin (1999) puts it:

> "Globalization, through global-scale linkages, disconnects the sources of demand from the location of production"

This global mechanism is of great importance for local land use allocation, insofar as landowners choose their production not only as a response to local economic opportunities, but also as a response to demand on the world market.

3.2. National policies and associated subsidies still prevailing

Developed countries such as the United States, and European countries with their Common Agricultural Policy (CAP), are however maintaining some level of barriers to trade, and more importantly, significant subsidies to their agriculture, in order to protect their economy and their farmers.

Hence, there are a lot of issues related to land use, many of them being of great importance for the future of humanity. Land use is thus an important concern in contemporary research.

The central importance of land transformation is indeed well recognized within the community of researchers concerned with global environmental change. Several research programs are focused on aspects of it; recent and substantial progress toward understanding these aspects has been made, and much more progress can be anticipated (Vitousek et al. 1997).

Land use allocation is associated with a lot of different, sometimes opposite-going mechanisms, which influence might be hard to assess precisely. Understanding land transformation is a difficult challenge; it requires integrating the social, economic, and cultural causes of land transformation with evaluations of its biophysical nature and consequences. This interdisciplinary approach is essential to predicting the course, and to any hope of affecting the consequences, of human-caused land transformation (ibid.).

In this report however, the focus is not on these drivers of land use change but on technical aspects driving demand, local environment,

4. <u>The modeling of Land Use</u>

4.1. Generalities concerning land use economics

4.1.1. The study of land-use, hypotheses, implications

Prior to reviewing land-use models, a brief examination of the study object – land – and its properties might help understand the underlying difficulties or hypotheses of land-use modeling.

Land use is indeed characterized by technical and physical properties, which will be taken into account in some way in models of land-use, but land also has to be considered as an economic good, *i.e.* an object which consumption, use, or possession increases utility, directly or indirectly. However, the study of land use differs from the study of other economic goods because of 3 characteristics: land immobility, land heterogeneity, and land property (that is, considerations of ownership, takings and rent seeking) (Parks and Hardie, 2003).

The consequences for the modeling of land-use are the following:

- There can be no land transfers over space;
- Land-use models need to account for spatial characteristics of land, and might need to take into consideration land heterogeneity over space;
- Land-use models might need to account for special behaviors due to particular types of land property.

4.1.2. “Non-maximizing” studies of land use

Historically there has been progress towards better taking into account adaptation in land-use modeling. Formerly, a 3-step approach was adopted to account for the effects of especially climatic change on agriculture:

(1) agronomic crop models were developed to simulate the effect of climatic change on crop yields
(2) yields were then adjusted to simulate crop-specific farm-level adaptations
(3) yields were then converted to supply changes in economic models

Further on we will give a few examples of technical and economic models following such a procedure.

(a) The production function approach

According to Mendelsohn and Dinar (1999), and Reilly and Schimmelpfennig (1999), the aim of models adopting the so-called “production function approach” is usually to estimate the impacts of climate change on agriculture, and more precisely on land values and farm revenues.

This kind of modeling is based on an underlying production function, also called crop-yield model. The estimation of the impacts of climate change on yields is derived by the variation of one or a few input variables, such as temperature, precipitation, and CO_2 levels, and the examination of the provoked change in yields. The estimation of the impact of climate change on revenues is derived from the simulated yields and exogenous prices.

However, such models tend to omit adaptation behaviors, such as switches of productions. And indeed, they de facto consider that the same crops continue to be produced at the same place despite the climate change. Consequently, these models can't be realistic and they are sometimes said to follow a kind of "Dumb farmer scenario".

(b) Agroeconomic analyses: Rosenzweig and Parry (1994)

This approach combines a biophysical and an economic study.

Rosenzweig and Parry's model aims as well at assessing the impact of climate change on yields.

It is based on data found on more than 100 sites worldwide, and was extrapolated to the whole world. Yields are averaged at the national level. The model only studies the impacts of climate change on grain crops (wheat, rice, maize and soybean).

A biophysical model simulates crop yields, which are then integrated in a world food trade model. A classical climate change scenario simulating a doubling of atmospherical CO_2 is then considered, and yield prediction under this scenario is derived by linear interpolation. Adaptation is taken into account by the application of ad hoc adaptation scenarios.

Compared to the traditional production function approach, this one uses a world food trade model which better accounts for the impacts of climate change on revenues, linear interpolation instead of the only biophysical model, and it takes into account adaptation, although poorly.

4.1.3. Limits of the non-maximizing approaches[9]

In the two approaches reviewed, land-use change assessment is limited by the fact that adaptation is poorly taken into account. This is due to the fact that economic behaviour of land managers is not precisely modeled.

However, in accordance with the neo-classical theory, behaviors in economics of land-use basically follow the same methodology and hypotheses as other economic goods: profit maximization, utility maximization and risk aversion (Parks and Hardie, 2003). Thus, economics of land use deal with optimal allocation of land, through land-use decisions, under the assumption that profit, or welfare, is maximized. Consequently, the modeling of the decision process of land managers is possible by writing the equations corresponding to profit maximization and risk aversion. By contrast, the two approaches reviewed previously can be called "non-maximizing approaches", because they don't take into account explicitly the maximization process.

[9] Reilly and Schimmelpfennig 1999, Mendelsohn and Dinar 1999, Mendelsohn et al. 1994

On the other hand, maximization equations have been formulated in different ways, and in multiple different attempts of land-use modeling. The “maximizing approach” is the kind of approach we are particularly interested in, in order to adopt it in our model of land use, because we want to focus on the process and results of land use allocation under certain variations in the economic or natural environment.

4.1.4. The Ricardian rent theory

The main underlying economic theory of land use economics used in the different types of land use modeling that we will present further on is the Ricardian rent theory. According to this theory, land-use choices are made through the optimization of land rent, which thus stands for the profit maximization behavior of land managers. Before presenting the Ricardian rent theory, a close look into the meaning of land rent is required.

The earliest definition of land rent is that of Adam Smith (1937):

> “(land rent is) the highest price a tenant can afford to pay the landlord for the use of land”.

Ricardo (1951, 1966)[10] studied profit rates determined within the agricultural sector, and he examined the role of differential rents in determining the margin of land cultivation:

> “it is only because land is not unlimited in quantity and uniform in quality, and because in the progress of population, land of inferior quality or less advantageously situated is called into cultivation, that rent is ever paid for the use of it”

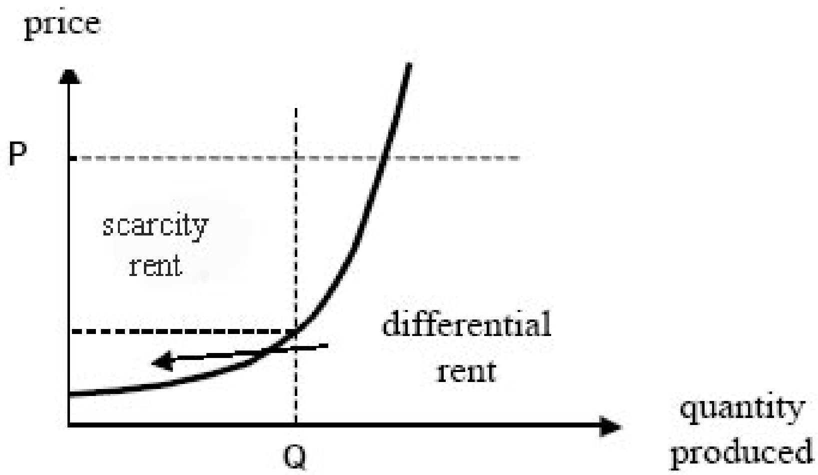


Figure 8. Marginal cost curve and differential rent and scarcity rents

According to the Ricardian rent theory, the price of an agricultural good (the product from the land, also called resource) is given by two different kinds of rent. The *scarcity rent* is not null when the price of the production is higher than the marginal cost of production. The *differential rent* is the surplus that emanates strictly from the production factor remaining, i.e. the land. The sum of these two rents is apprehended under the concept of *resource rent*, as the figure above indicates.

[10] Ricardo David, 1817, Des principes de l'économie politique et de l'impôt.

This theory is useful in the modeling of land use, insofar as economic models allocate land according to its relative economic return under different uses. The economic return of land is measured as the resource rent. Land is supposed to be used by land managers in order to maximize the resource rent.

4.2. What questions are addressed in land-use modeling?

According to Lambin et al. (2000), on designs a land use model specifically to answer some precise question(s). The environmental and cultural variables, the geographical scale and the regions, and the time scale, which are chosen for the model, totally depend on the problematic addressed by the model.

And indeed, in the literature, we have been able to distinguish different categories of questions in the models we reviewed.

4.2.1. "Economic, profitability" question

- Problematic:

Will agriculture be able to sustain economically some changes; will it continue to be profitable?

- Sources:

Literature about adaptation and vulnerability of agriculture: Mendelsohn et al. (1994), Rosenzweig and Parry (1994), Darwin (1999), FASOM (McCarl 2004), AROPAj (Bamière et al. 2005).

- Context:

These issues are raised particularly in the context of climate change and also public policies (e.g. carbon policy in the case of FASOM) etc.

- Other related questions:

What regions will be most affected, in what regions agriculture is most vulnerable? In which regions agriculture is the most likely to adapt the best from an economic point of view to changes in the natural or socioeconomic or political environment?

4.2.2. "Quantity, nutrition" question

- Problematic:

Will agriculture continue to be able to produce enough food for everybody despite changes in the natural, social, economic, political environment?

- Source:

IMPACT (Rosegrant et al. 2005), IMAGE (Alcamo et al. 1994)

- Context:

Global pollution, climate change, competition between different economic uses of land.

- Related questions:
  - Concerning changes in production areas: what regions will be able to produce food in the future, where will be the big production basins?
  - Concerning competition between different economic land uses: between agriculture and forestry, between agriculture and urban areas, between food production and plants used as biofuels, between food and animal feed production. How will different interests for land use compete, and how, in this context, agriculture will continue to be able to feed the world?

4.2.3. Impact mitigation

- Problematic:

How can we reduce the impact of agriculture on the environment?

- Source:

AROPAj (Bamière et al. 2005), IMAGE (Alcamo et al. 2005)

- Context:

Local pollutions, climate change, need to find adequate policy measures.

Retrospectively, there is no unique way to answer a given question; each model chooses a specific viewpoint, and focuses on some particular aspects of the problem. Different models might not give exactly the same answer to a given problematic, but the comparison between methodologies and results allows for a better understanding of the underlying phenomenon that is studied.

4.3. How can we classify land-use models?

4.3.1. Why a review of models and classification?

In this part we make a review of some existing models of land use allocation. The goal of such an exercise is multiple:

(1) to find in each model its specificity,
(2) to figure out how the problematic answered by each model relates to our own problematic,
(3) to figure out what elements were found pertinent by the authors to answer their problematic,
(4) to assess what elements we find pertinent can easily be reproduced in our model
(5) to assess what the limits are in the models we study
(6) to find what improvements we should try to make compared to the preexisting models

To make it easier to understand, it is always useful to classify the models we present.

There is a great variety of modeling approaches and applications. There have been different attempts to classify these modeling approaches. We have decided to follow roughly the classification by Heistermann et al. (2006a) for continental and global land-use modeling. In their classification, the guiding principle is the integration of geographical and economic modeling approaches.

The models presented are all at least regional. The global scale of our study makes small scale models undesirable, according to Heistermann et al. (2006a), because:

- Many important drivers and consequences of land-use change are of global extent
- Specific processes interlink locations and regions all over the globe
- Land-use changes and environmental impacts are often spatially and temporally disjoint

This model review falls into three main parts: geographical models, economic models, and integrated models. Each part is further subdivided according to differences in methodology, in key mechanisms, in scale precision or in the representation of the economy.

4.3.2. Geographical models

Geographical models focus on the process of land-use change itself. They develop spatial patterns of land-use types, each of which has a special allocation of area or commodity demand, by analyzing land suitability. "Suitability" is based on local characteristics of land and spatial interaction with other parameters (climatic, social, economic etc.). Thus these models don't explicitly take into account the mechanisms of allocation of land-use. A further classification is possible, according to the key mechanisms used to simulate the process of land-use change: the "empirical-statistical" way, vs. the "process-based" way (Heistermann et al. 2006a).

4.3.2.1. Empirical-statistical models

Empirical or statistical models locate land-cover changes by applying multivariate regression techniques to relate historical land-use changes to spatial characteristics and other potential drivers.

Example: Ricardian rent model (Mendelsohn et al. 1994)

This is a regional, statistical model, which applies to the United States only.

It aims at assessing the economic impact of global warming on US agriculture, and more precisely the impact of climate on land prices or revenues. Basically, in this model, climate impacts on net rent or value of farmland are evaluated by measuring farm prices or revenues.

Concretely, land-use is represented by land values, insofar as they are supposed to stand for a certain set of crop productions, and climatic, geographic, and socioeconomic characteristics. The observations are weighted by the percentage of each county in crop-revenue, which puts emphasis on counties that are most important to total agricultural production, that is, truck farms and citrus belt. This way to take into account crop production is considered representative of the agriculture profitability or value in the country.

Regressions of land values on climate, soil, and socioeconomic variables are performed so as to estimate the best-value functions across different counties, that is, the effect of existing climate on property values. Hence land suitability is represented by a relationship between land values and spatial and climatic variables.

The climatic variables are changed to simulate global warming, and the effect on land values is derived from the equation previously defined. The climate change scenario applied is the conventional doubling of the atmospheric CO_2, translated to the US into a uniform 5°C temperature increase and 8 % precipitation increase per US season and region.

The economic impact is measured in terms of economic costs per sub-region in the US. The model doesn't provide information about specific change in land allocation, it only indicates, through the change in land revenue, that land-use has changed, and it is able to quantify the cost of change. However, if a certain type of land use is associated to certain land revenue, then land uses might probably be deduced from the land revenues, although with a high level of uncertainty.

The main limit of such models is that long term projection is difficult, because empirical relationships can't be assumed constant over long time periods.

4.3.2.2. Process-based models:

These models describe biophysical and technical processes of land-use change. The methodology used, described in Heistermann et al. (2006a), who cite namely the works of Stephenne and Lambin (2001) and Cassel-Gintz and Petschel-Held (2000), consists in focusing on a sequence of agricultural land-use changes. The aim of this approach, also referred to as the "syndrome approach" is to identify a causal chain, by combining spatially explicit and quantitative data sets with qualitative reasoning. The causal chain might ideally be recognized as also being relevant in other parts of the world. This identification work enables the provision of global scale patterns for the occurrence of, and susceptibility to specific types of land use changes. Thus, the syndromes approach provides information where specific land-use changes might occur, and what precisely they might be. However this kind of model can only apply to regions where very precise elements corresponding to a certain pattern of land use change, already observed elsewhere, have been identified. This approach could basically be integrated into a quantitative framework in order to model actual land-use changes, but it can't be generalized alone to any region of the planet.

4.3.2.3. Advantages and limits of geographical models:

Geographical models take well into account local biophysical and socioeconomic constraints, as it is their main focus.

However, in such models, land-use change mechanisms are not explicitly modeled and the causal relationships are not clearly established. In fact, these models can only predict patterns of land use changes which are represented in the calibration dataset. That is to say, they are only able to predict some specific changes in land use where such changes have been measured over the recent past. Thus these models are unable to make long-term projections, and they cannot be used for wide-ranging extrapolations (Heistermann et al. 2006a).

4.3.3. Economic models

These models focus on drivers of land-use change on the demand side. They allocate land-use based on supply and demand of land-intensive commodities, which are both computed endogenously. Land is not the focus of interest, but was introduced mainly in order to facilitate an assessment of environmental problems such as climate change (Heistermann et al. 2006a).

The economic models are further discussed by Heistermann et al. (ibid.) along general economic modeling concepts and strategies to introduce land and land-use dynamics. Economic land-use models differ in sectoral and regional resolution, and in the representation of trade and land.

4.3.3.1. Partial equilibrium models

(a) Little sectoral resolution: AgLU (Edmonds 1996, and Sands et al. 2003)

AgLU (Agricultural and Land Use model) aims at simulating global land-use change and the resulting carbon emissions over one century in response to a carbon policy.

It is a global, top down, partial equilibrium economic model of land use, where the world is divided into 11 regions. The model is programmed to find the best land use distribution that enables the equilibrium between demand and supply.

Land use is represented through one composite crop, 2 types of forest products, one type of pasture and one category of animal products. A system with more crops is being developed.

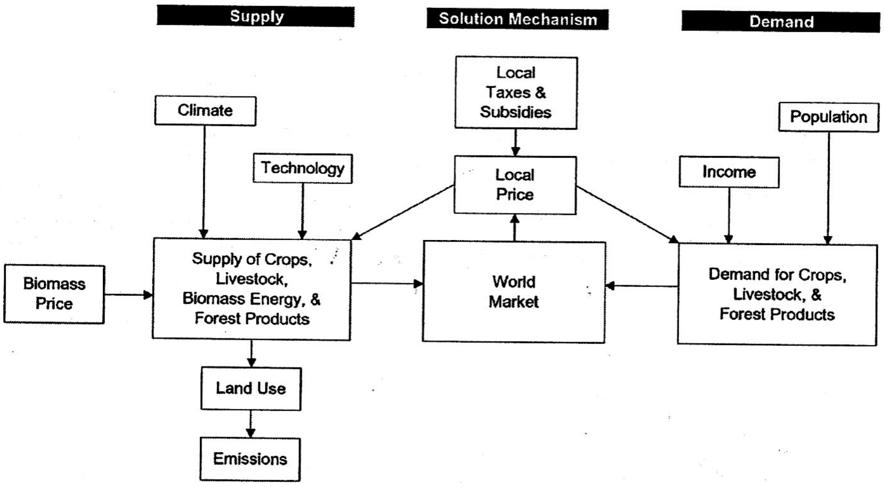
From an economic point of view, AgLU has 14 prices determined by 14 non linear equations that equate supply and demand in each market. These markets are the following:

- 1 world market for the composite crop (that is to say, one world price brings global supply and demand into equilibrium)
- 11 regional markets for the composite animal product (regional supply must equal regional demand, adjusted for trade in animal products between regions)
- 1 world market for the composite forest product
- 1 world forward market for the composite forest product (because of the time lag between planting and harvesting trees)

Land is allocated among crops, biomass, pasture, forest, or remains unmanaged, according to the economic return from each land-use type in each region. A joint probability distribution is defined over yield in each alternative land use. Carbon policies are simulated in the model by the introduction of an exogenous carbon price.

Demand for crops, animal and forest products, is a function of prices, per capita incomes, and population. For food categories (crop and animal products), diet is considered as an exogenous input by region and food category. Demand for biomass is represented through a price for biomass computed exogenously.

Figure 9. AgLU model structure (Sands et al. 2003)



The model then provides estimates of carbon emissions from land-use change over the next century in response to changing populations, incomes and agricultural technologies

The limits of such a model stand in the fact that it is not spatialized; it is rather based on a simple probabilistic structure which doesn't capture the true variability of land within a region. It proves difficult to match the parameters of the joint probability distribution used by AgLU with the large amount of data available on soil and crop productivity.

(b) Higher sectoral resolution and geographical precision: IMPACT (Rosegrant et al. 2005)

IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) is a global scale model. However it incorporates modules with a variety of spatial scales, from river basins, countries and more aggregated regions, to the global level. It consists of 36 countries or regions, and 69 river basins. Food demand and trade are modeled at the national level.

This model aims at analyzing the effect of population, investment and trade scenarios on food security and nutrition status. It studies the linkage between the production of key food commodities and food demand and security. IMPACT is also concerned with the fact that long-term change in water demand and availability, and variability in rainfall and runoff, has an important impact on food production.

The agricultural products are disaggregated into 16 crop types, 6 livestock and poultry types (including eggs), and 10 fish or sea products. Yields are estimated for each country or region, and are assumed constant throughout the country or region. Yields are linked to producer prices and prices of production factors, technological improvement (constant growth rate) and water stress.

Within each country or regional sub-model, supply is determined by the area and the yield response function (the obtained yield and the harvested area depend on exogenous parameters). Domestic demand for a commodity is the sum of its demand for food, feed and other uses. Prices are endogenous in the system of equations for food. Domestic prices are function of world prices. Country and regional sub-models are linked through trade. The key mechanism involved in the model is the minimization of the sum of net trade at the international level and the satisfaction of market-clearing condition.

The specificity of this model is its taking into account water availability in the formation of yields (see 6.5.2.1, p.82, for a precise description). However, water is considered at a too coarse scale to be able to bring a significant degree of precision. The precision in the representation of yields is also very low, as yields are averaged at the national level and assumed to be constant.

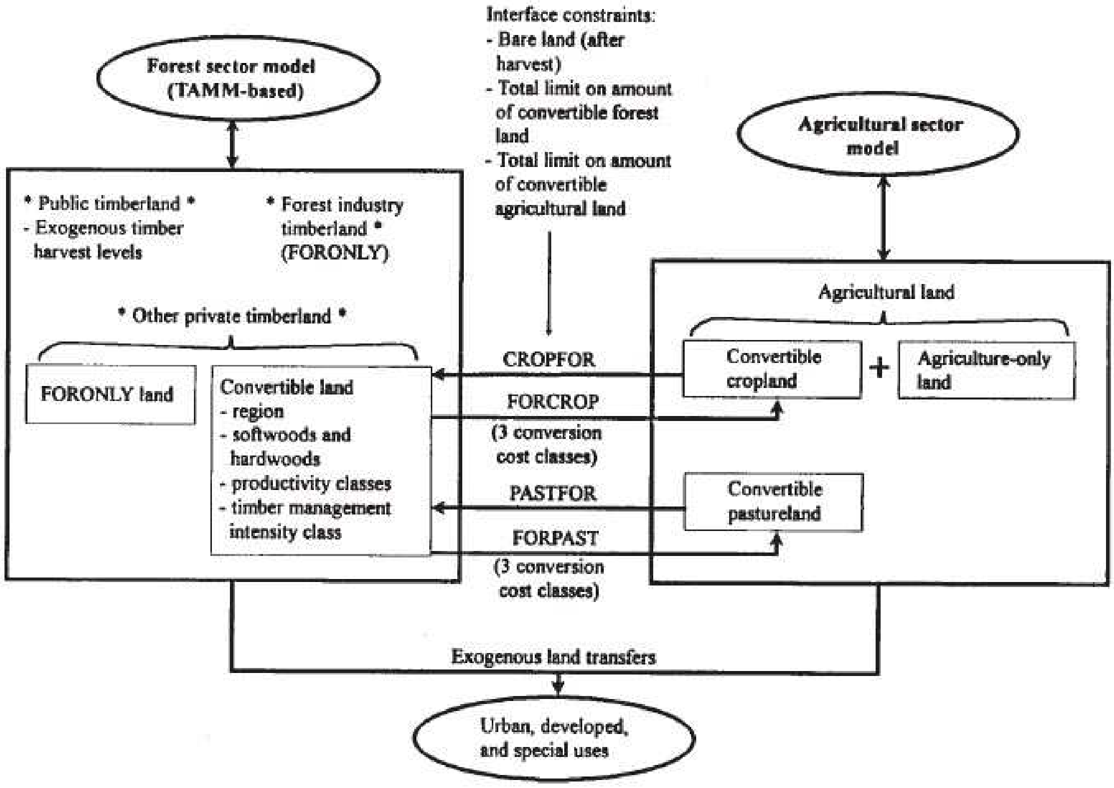
(c) Higher geographical precision: FASOM (Adams et al. 1996; McCarl 2004)

FASOM (Forestry and Agricultural Sector Optimization Model) is a dynamic, nonlinear programming model of the forest and agricultural sectors in the US.

Its objective is to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees.

FASOM's study area is the US, which is subdivided in 11 homogenous supply regions (Alaska and Hawai are excluded). Some regions don't have any forest. One doesn't have agriculture. There is one single national demand region.

Figure 10. FASOM model structure (Adams et al., 1996)



Crops compete regionally for land, labor and irrigation water. 36 primary crops and 39 secondary products are represented. The model simulates market behavior over 100 years with a decade-long time period. There are more than 200 production possibilities representing agricultural production in each decade. These include field crop, livestock, and tree production. The field crop variables are divided into irrigated and non irrigated production according to the irrigation facilities available in each region.

The decision making process for land use allocation is the maximization of the net present value of the returns from the activities performed on a given land. The model takes fully into account competition between forests and agriculture for land use. The objective is to maximize the present consumers' plus producers' surpluses net of transport and capacity costs.

The model is constrained so that for each area, the crop mix falls within one of the mixes observed in the the past 20 years (just for the first two decades). This prevents unrealistic complete specialization of some regions, for which the optimal solution would be a single crop budget. Land use and exchanges of land between sectors in some of the regions are constrained for empirical or practical reasons.

What is more, farmers and timberland owners are modeled as being able to foresee the consequences of their behaviors. They are said to have a “perfect foresight”.

This model appears to have the highest precision in terms of crop disaggregation, yield representation and geographical scale.

But it encounters a few limits:

- Only managed forests, which produce revenue from wood exploitation, are considered.
- Tree growth is not modeled; harvest takes place once per decade, whereas agricultural markets are held every year.
- Simulations can be done over a 100 year period of time, but the sequestration policy is assessed only over the first 50 years.

4.3.3.2. Computable general equilibrium models (CGE)

In such models, contrary to partial equilibrium models which consider only the agricultural and forestry market, all markets are modeled explicitly and are assumed to be in equilibrium in every time step. All money-flows are traceable throughout the whole economy and the structure provides the emergence of feedback effects between sectors. CGEs are often used to analyze the effects of changes in single sectors on the entire economy and vice versa (Heistermann et al., 2006a).

Example: GTAP Global Trade Analysis Project (Brockmeier 2001)

The GTAP model is a multi-regional, static, applied general equilibrium model. The underlying equation system of GTAP includes two different kinds of equations. One part covers the accounting relationships which ensure that receipts and expenditures of every agent in the economy are balanced. The other part of the equation system consists of behavioral equations which based upon microeconomic theory. These equations specify the behavior of optimizing agents in the economy, such as demand functions. Thus the agricultural sector is figurated by a representative producer for each agricultural sector of a country or region. Each producer chooses inputs of labor, capital and intermediates to produce a single sectoral output so as to maximize a profit function. In the case of crop and livestock production, farmers also make decisions on land allocation.

The GTAP structure can be described as follows. The starting point is a regional household associated with each country or composite region of GTAP. This regional household collects all income that is generated in the closed economy. Producers are also part of this framework. The firms and the regional household together build a closed economy, linked together by economic flows, consisting of taxes, savings, expenditures and revenues. The regional economy faces the rest of the world, consisting of the 86 other regions taken into account in the model (GTAP version 6).

GTAP assumes that land is heterogeneous. The heterogeneity is introduced by specifying a transformation function, which takes total land as an input and distributes it among various sectors in response to relative rental rates.

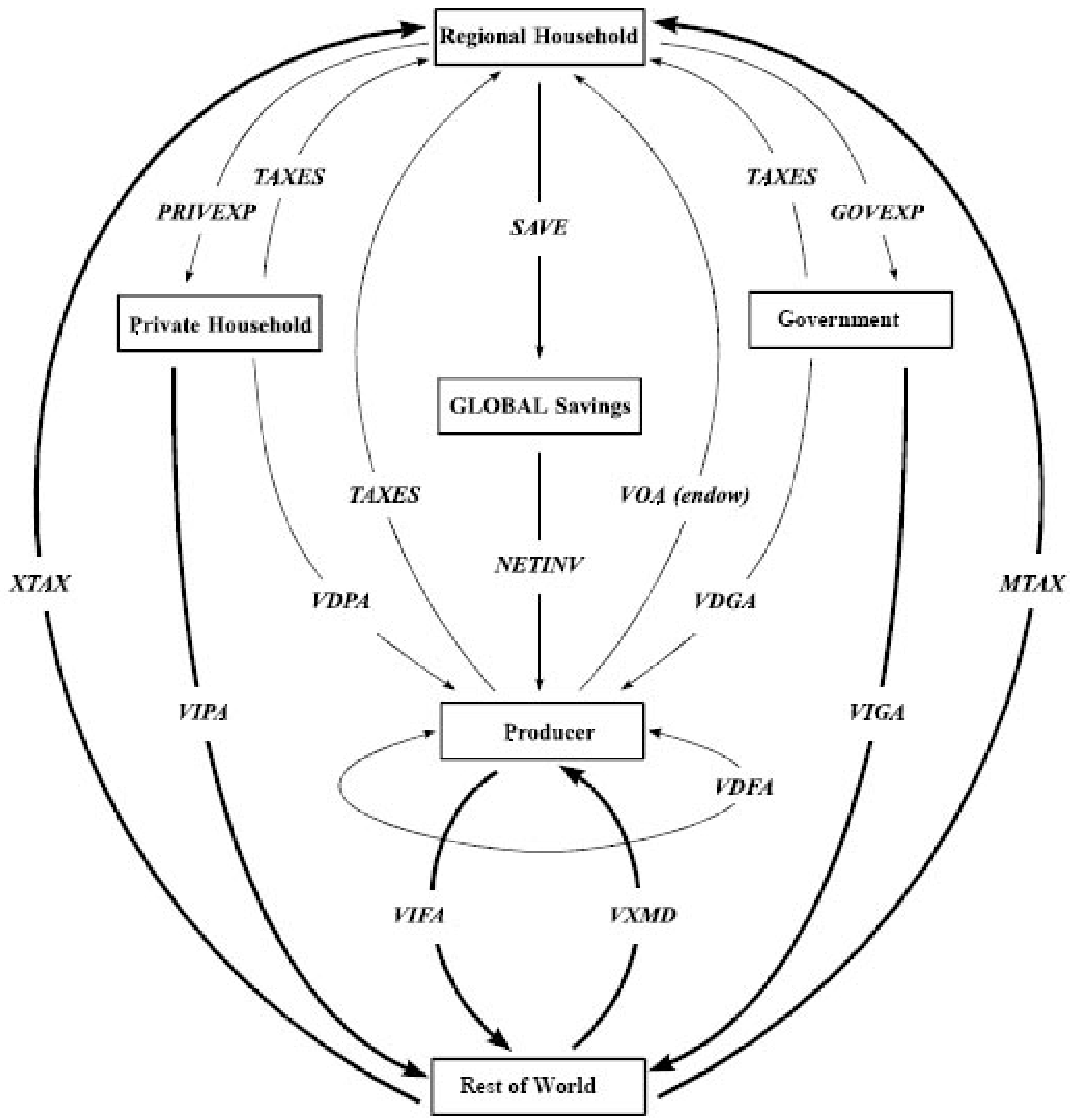


Figure 11. GTAP model structure (Brockmeier 2001)

Economic equilibrium models can consistently address demand, supply and trade via price mechanisms. However, they are limited in accounting for supply side constraints, in reflecting the impact of demand on actual land-use change processes, and in representing behaviors that are not related to price mechanisms.

It should be noted that optimization models such as GTAP are frequently used as components of integrated models, which we will examine in the following chapter.

4.3.4. Integrated models:

Integrated models combine an economic analysis of world markets and policies in order to quantify demand and supply of land-intensive commodities, and the actual allocation of land-use to locations based on a geographic analysis. Concretely, they generally consist in the coupling of economic optimization models (such as GTAP) with tools for spatially explicit evaluation and allocation of land resources.

4.3.4.1. Activity based or farm-based models: AROPAj model

In these models, the agricultural production is broken down into different farm types or production systems (in their great variety).

This model, developed by the INRA (described in Bamière et al. 2005), is a microeconomic partial equilibrium model, with an exogenous demand. It aims at anticipating the consequences of the continual reform of the CAP and at evaluating the environmental impact of such changes.

AROPAj consists of a set of independent, mixed integer and linear-programming models. Each model describes the annual supply choice of a given farm type, representative of a group of farmers. Each farm-type accounts for a certain set of technical constraints and consists of the aggregation of farms located in the same region, characterized by similar type(s) of farming and belonging to the same elevation classes. The decision making process is modeled by the maximization of the total gross margin in each farm type group.

4.3.4.2. Sectoral models

In sectoral models, as opposed to activity-based models, agricultural production is broken down into different crop and livestock production types, regardless the production systems in which the crop are grown.

(a) Example: the agro-ecological approach FARM (Darwin et al. 1995)

FARM (the Future Agricultural Resources Model) combines a biophysical and economic study. The FARM framework uses a GIS to link climatic variables with agricultural production and land rents.

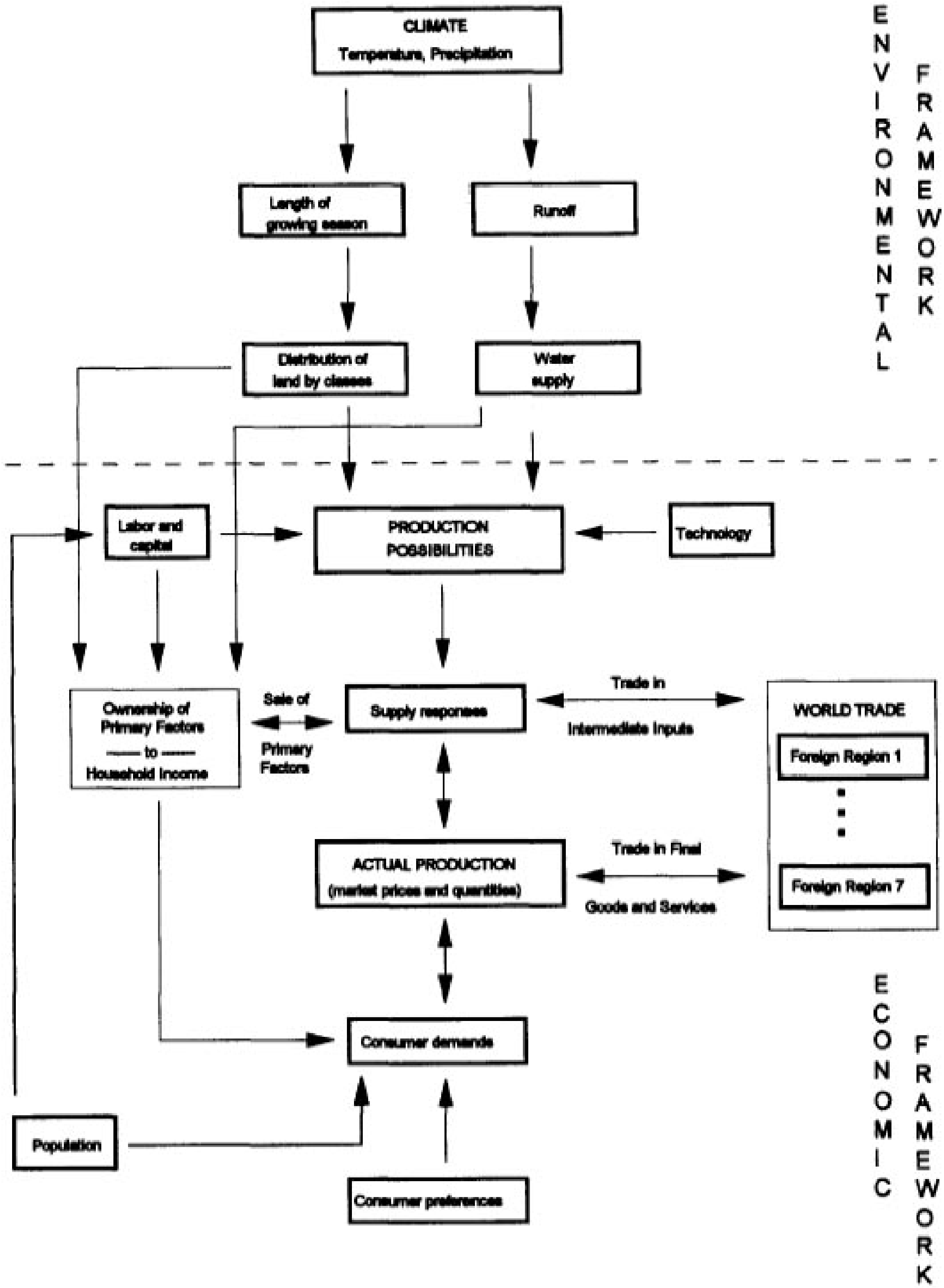


Figure 12. FARM model structure

In their study, Darwin et al. assess the impact of climate change on agricultural production. More precisely they study how climate change contributes to the shift of land classes worldwide, and they derive the shift of production regions.

FARM's GIS divides the world into twelve geographic regions. Climate is captured by six land classes, each of them with some particular production characteristics consisting of a mix of crops, livestock, and production levels. Land classes are determined by a length of growing season[11], water holding capacity, a production level, costs, and an input use.

FARM's economic framework consists of a multi-region, multi-sector, CGE model. The CGE model accounts for all domestic and international money flows. Households use the revenues from the sales of the four primary factors of production (land, water, labor, and capital), to purchase consumer goods and services from the producing sectors in domestic and international markets.

The CGE model contains 8 regions. Each region has 11 producing sectors – including crops; livestock; forestry; and processed foods. The crop sector is the only one to be multi-output, producing wheat, grains, and non-grains. All regions produce, consume, and trade the 13 commodities.

A region's primary factor endowments of land, water, labor and capital are determined exogenously and are region-specific: i.e., one region's primary factors cannot be used by another region's sectors. Land is in fixed supply.

Water, labor, and capital are homogenous, i.e., within regions these factors are perfectly mobile across all economic sectors, and each has one regional price. Regional supplies of these factors are perfectly inelastic. Water is supplied to the crops, livestock, and service sectors. Land, labor and capital are supplied to all sectors. Regional demands for water, land, labor, and capital are sums of sectoral demands.

Producer behavior in FARM is driven by profit maximization assuming competitive markets. The impacts of climate change on land use are simulated by estimating the regional change in water supplies and the distribution of land classes under a new climate. These changes, which are computed in FARM's GIS, are derived from changes in mean monthly temperature and precipitation generated by general circulation models, which mathematically simulate global weather and climatic processes over time for given levels of atmospheric carbon dioxide. Scenarios of population growth and global trade policies are also tested.

(a) Example: IMAGE (Alcamo et al. 1994)

IMAGE (Integrated Model for the Assessment of the Greenhouse Effect) is a multidisciplinary and integrated model. The model applies to the whole world, subdivided in 13 world regions based on economic similarities, and along a grid of 0.5° latitude by 0.5° longitude for biophysical properties.

The objective of the model is to simulate the dynamics of the global society-biosphere-climate system, to investigate linkages and feedbacks in the system and to evaluate consequences of climate policies.

[11] Length of growing season is defined as the longest continuous period of time in a year that soil temperature and moisture conditions support plant growth (Darwin et al. 1996).

IMAGE consists of 3 different sub-systems: the energy industry module, the terrestrial environment module, the atmosphere ocean module. Within each module there are different models simulating atmosphere, land cover, economy etc.

The Land Cover model (LCM) simulates land cover transformations on a global grid. It uses inputs from the Agricultural Economy Model (in the form of regional demands for cropland and rangeland), from the Energy Economy Model (regional demand for fuelwood), from the Terrestrial Vegetation model (local potential of land). Agricultural crops are computed all together in one unique agricultural land category.

The economic dimension is given by the Agricultural Economy model (AEM). Food products are associated with so-called intensities, which indicate the amount of land needed to supply 1 Kcal per day of the vegetative or animal product, taking into account the conversion from feed to meat. Because prices do not exist in the AEM, intensities are considered to be a proxy for prices. The heart of the AEM consists of 13 regional utility functions, which return a utility-value for a given diet. The maximum value is achieved at the point where the demands are equal to the so-called preference levels. The key-mechanism of the AEM is to optimize the utility function, given a budget, which is a function of intensities, income, average potential production and technology. IMAGE uses as inputs different SRES[12] scenarios defined by the IPCC[13].

Regional-scale changes in agricultural demand, given by the AEM, are satisfied in the LCM by changing land cover anywhere within the region, depending on the most suitable location for a particular land use. This is a simplification compared to reality, because land-use change is also affected by local and national economic factors. Land suitability is defined according to the land productivity, the proximity to already existing agricultural areas, and to water resources. Thus the LCM takes partially into account constraints of accessibility to water resources, and can provide a plausible geographical distribution of land uses within regions, contrary to other global models.

IMAGE is unable to provide grid scale calculations for all components of climate change – in particular for economic calculations. It indeed has problems for specifying economic and demographic factors on a country or sub-country scale for the entire world over the long time horizon of the model.

There is quite a big discrepancy between the results of the terrestrial vegetation model and reality in regions where the vegetation and the agricultural distribution depend on causes other than climatic (e.g. additional water storage and supply, anthropogenic influence and natural disturbance).

Finally, the use of intensities as proxies for prices is very questionable.

4.3.5. Main conclusions on the reviewed models

The models that have just been reviewed can be distinguished along various criteria. The way they have been classified is just one of many. This review has outlined the factors that might need to be considered when developing future land-use change models:

[12] Special Reports on Emissions Scenarios (IPCC, 2000)
[13] IPCC: Intergovernmental Panel on Climate Change

- The geographical and socio-economic context
- The spatial scale
- The sectoral precision (horizontally speaking – e.g. various types of crops, forests, and vertically speaking – the various transformation pathways)
- Temporal issues such as dynamic versus equilibrium models, thresholds and surprises associated with rapid changes
- System feedbacks (the models reviewed take account at best partially feedbacks of the environment in the agricultural system, in terms of changes in yields for example)

We shall now go back to a few specific considerations about some types of models.

4.3.5.1. Partial equilibrium models

In partial equilibrium models, the geographical scale allows a high level of detail in the modeling of land characteristics. The high level of disaggregation that is thus adopted implies high data requirements. As a consequence, although the modeling of local land-use changes is made very realistic, it is difficult to make the model grow beyond the regional scale. In particular in the case of FASOM, the exclusion of links to international markets for forestry and agricultural products, and the absence of markets for other goods, make it less suited to study long run effects of more general or global policy, although it is very well suited to study specific national policies aimed at forestry or agriculture.

Thus, in retrospect, partial equilibrium models seem to be a good tool to study local or short-run policy questions, when there is no need to look at international effects or general equilibrium effects. If the problem under scrutiny has a long-run or international dimension, one might need to take into account general equilibrium effects.

4.3.5.2. General equilibrium models

The generally large geographical scale of the general equilibrium models prohibits a too detailed modeling of the biophysical features of land, contrary to partial equilibrium models. However, the general equilibrium seems to allow for studies of sectoral and regional interactions through changes in relative prices, and for studies of the role of much wider-sectoral and geographical -scope policies. General equilibrium models are capable of coping pretty well with questions regarding the long-run. By contrast, some parameters which are considered as given and fixed in partial equilibrium models have to be considered as changing in the long-term, and thus be integrated in feedback loops if one wants to study the long-term.

At any rate, the best model to answer a certain question depends on the exact scope of the problem. The important features to take into consideration when one has to choose a type of model are: the geographical scope of the study, its time horizon, the scope of the policy studied (Van der Derf and Peterson, 2007).

4.3.5.3. Considerations about the decision making process of land users

The distinction between farm-based and sectoral models stresses the fact that economic decisions are taken at the farm-level, and not at the level of a geographic area. Thus farm-based models such as AROPAj seem to represent the best the economic decision process. However one doesn't always need to represent the economic decision process at the level of an individual farm. At an aggregated level, the economic decision process can very well be represented by the maximization of the regional revenue for each crop instead of for each farm.

It is worth mentioning the arbitrary definition of the objective functions, as maximizing the land rents. This definition, inherited from Ricardo as we have seen previously, might deserve a closer attention. People are indeed found to adopt sometimes non-optimal behaviors, due to differences in values, attitudes and cultures. At an aggregated level, these limitations are likely to be non-significant, however they are more important as one looks at fine scale land-use change processes and as one is interested in the diversity between actors (Lambin et al. 2000). Some authors mention possible drivers of land use change, other than profit maximization, that are likely to have a significant impact and are not often taken into account in the traditional models:

- population growth and farmers' assumed preferences for leisure
- goal to provision the household, maximization of utility with a trade-off between consumption and leisure, and limited market integration

Turner et al. (1993) stress the importance of using evidence from case studies to supplement the modeling activities. And indeed, evidence from case studies can provide useful information on the drivers of land use change, and help to assess the accuracy of the model.

This is just to remind the reader that one should not consider the mechanism of land use allocation as obvious. The choice of land rent maximization as the key decision making process is questionable. However it has proved to be powerful enough to represent accurately decision behaviors at an aggregated level.

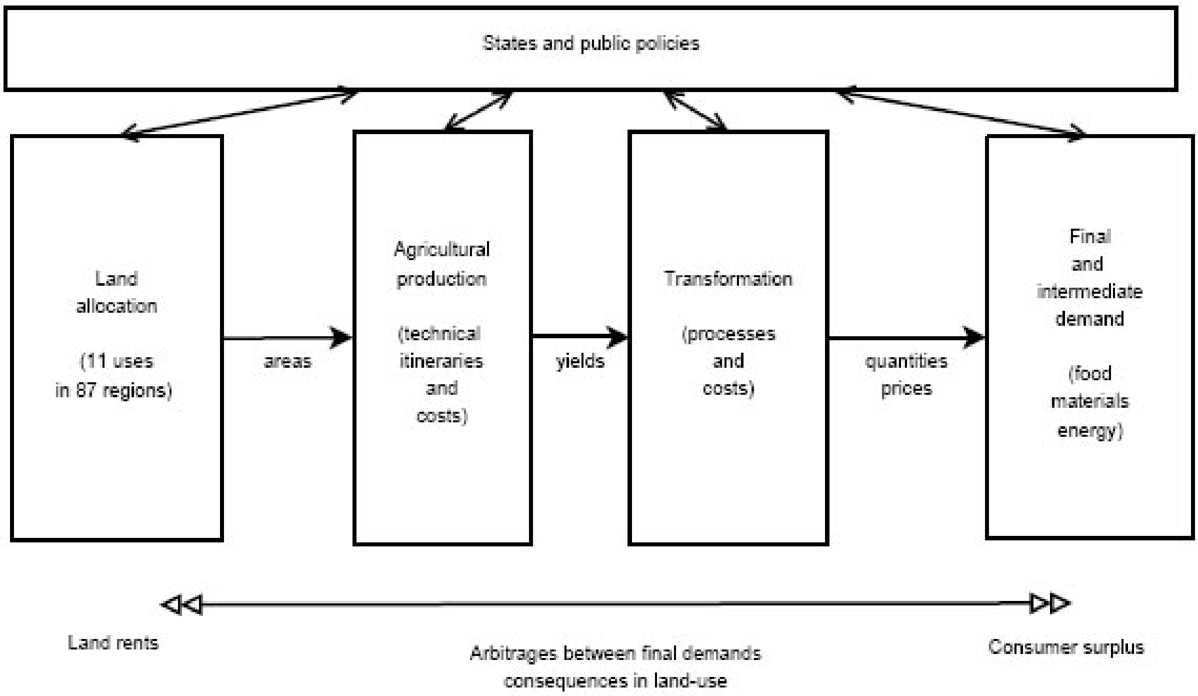
4.4. Nexus-Land Use model

Dans quelque domaine que ce soit, la perfection est enfin atteinte non pas lorsqu'il n'y a plus rien à ajouter mais lorsqu'il n'y a plus rien à enlever.
Antoine de Saint-Exupéry, 1900-1944

4.4.1. General description

We shall focus here on a rapid and schematic description of the supply side of the agricultural part of Nexus Land Use model. For a more precise description, especially on the forest module and on costs, refer to Gitz and Ollivier (2007). The Nexus Land Use model is an economic model of optimal land use allocation. It was developed with the CIRED[14], based on works by Marie-Hélène Hubert and Hélène Ollivier.

Figure 13. Schematic representation of the Nexus Land-Use model (Gitz and Ollivier 2007)



Nexus is a partial equilibrium sectoral model, combining different production channels. It is decomposed in three parts: the primary production, the industrial transformation and the final consumption. The first step considers the land-use decisions, the second the mix of natural inputs and the third the consumption bundle. This model is developed to assess the impacts of the evolution of demand on the competition between the different production options. But as

[14] Centre International de Recherche sur l'Environnement et le Développement

it is intended to be as complete as possible, it should eventually be able to address some issues of global importance such as competition for land use between energy and food production, impacts of climate change on land use patterns and food production, and contribution of agriculture to climate change, distribution of agricultural revenues under new agricultural patterns.

The key mechanism of Nexus is the maximization of net social surplus, in all lands and in all regions, by a benevolent planner, to meet a given regional demand. The optimization functions with endogenous prices are determined by land rent, by relative prices of the transformation products and by consumers' prices. Simulations are made by incorporating trends according to long-run scenarios. At each time step, Nexus computes optimal shares of land uses.

The choice of a partial equilibrium model was made because this kind of model is less complicated to deal with, and allows for more precision in the field it focuses on, that is, agriculture in this case. However, in the long run, Nexus is meant to be coupled with a general equilibrium model developed by the CIRED and called ImaclimR.

This model's originality is to take into account in a dynamic fashion forest and agriculture, and above all to allow for changes in the frontier between these two uses. This model has the following characteristics:

- It is an economic model, thus it follows the rule of surplus maximization
- It is a global model
- It encompasses primary and secondary forests and plantations
- It includes agriculture
- It is dynamic
- It includes details on the processes of production and transformation of agro-forestry products

4.4.2. Nexus regions

Nexus uses a world disaggregation in 87 GTAP regions (version 6). These regions are then reaggregated in two different ways. This aggregation choice was imposed by the research of data and parameters for the model. Nexus thus uses 3 different kinds of disaggregations:

- Disaggregation in 87 regions from GTAP 6
- Nexus type disaggregation in 7 regions, which stand for the demand centers: East Asia, Industrialized Countries, Latin America, North Africa, Sub-Saharan Africa, South Asia and Transition Countries;
- Disaggregation is 14 regions stemming from Sohngen et Al. (1999), which determine the dynamics of forest growth of the model: South East Asia, Central Asia, South Central America, Africa, Europe, China, South Korea, Russia, India, Australia, Canada, Japan, New Zealand, and the United States

4.4.3. The supply side

4.4.3.1. Agricultural land use

The supply side of the model consists in products from agriculture and forestry.

Land use is disaggregated at different levels: first, agricultural land uses are opposed to forest land uses; second, agricultural land uses are decomposed in croplands, pastures and fallow; third, forest land uses contain planted forests and managed forests.

Nexus distinguishes between 3 forest types: planted forest, managed or secondary forest, and sink or primary forest. As our focus is on agriculture, we won't give more detail on the forestry part of the model. Agricultural land uses contain paddy rice, wheat, cereal grains, vegetable and fruits, oil seeds, sugar cane and sugar beet, plant-based fibers, other crops (all adopted from GTAP 6), plus pasture and fallow.

4.4.3.2. Primary productions

The production of an agricultural primary output (po), in a production region r , is described by the following equation:

$$Q(po,u,r,t) = L(po,u,r,t) \cdot y(po,u,r,t)$$

Where :

- u refers to the land use category devoted to this production
- r refers to the production region
- $L(po,u,r,t)$ refers to the part of the available land in the region r devoted to primary production of po at time t
- $y(po,u,r,t)$ refers to the average yield of po in the region r at time t

4.4.3.3. Primary product transformation

Primary crop production is then devoted to human food or introduced in the animal production mode to produce feed.

In order to produce final food commodities, the food industry sector proceeds in two stages: first of all, the primary agricultural activity of production, then the industrial activity of transformation. This last operation implies a raw material loss; therefore the quantity of agricultural production is divided by a conversion rate.

The case of meat production is similar to industrial transformation, but it can be achieved through two different production systems: intensive through animal feed production, or extensive via the pasture mode.

For the extensive grazing production, the average output in terms of ingerable biomass, coming from the region r, denoted by $Q(pastures,r,t)$ amounts to:

$$L(pastures,r,t)\cdot y(pastures,r,t)$$

Then the livestock output from pastures, in terms of carcass weight, is:

$$Q(Carcass_a, pastures,r,t) = Q(pastures,r,t)\cdot \lambda_1(pastures,a,r,t)$$

Where a refers to the animal type and λ_1 is the feed ratio (in tons of carcass weight per ton of dry matter). For the intensive production system, the equations are similar, but with quantities, yields and feed ratios corresponding to feed crops.

Once the livestock output is obtained, the carcass weight is considered as an input for the meat and dairy transformation process, which is identical for both production systems. The final meat and dairy products are obtained by the use of a transformation coefficient.

Costs are obtained thanks to constant average production costs by region, final output, and at a given time.

4.4.4. The demand side

The demand side is represented by demand functions specified for various centers of demand. The drivers of the demand side are based on exogenous scenarios of growth and diet change.

In this respect, Nexus Land use follows a I = PAT scheme of the effects of driving forces, which was first described by Ehrlich and Ehrlich and by Commoner (Meyer and Turner 1992). In this approach, I stands for impact, P for population, A for affluence, and T for technology.

Nexus' centers of demand are defined as subsets of the considered regions and countries, and noted k. For a good j, the demand function is defined as following:

$$D_{jk} = A_{jk}\cdot P_j^{\alpha_{jk}}\cdot Y_k^{\beta_{jk}}\cdot N_k$$

Where:

- D_{jk} is the demand of good j in the center of demand k, expressed in millions of tons
- A_{jk} is a technical coefficient specific to each good
- P_j is the world price of good j in dollars per ton
- Y_k is the GDP per capita (in the center of demand k) in dollars
- N_k is the population in the center of demand k

α_{jk} and β_{jk} are respectively the price and income elasticities of demand of good j.

The final world demand for the final food commodity j is thus $D_j = \sum_k D_{jk}$.

4.4.5. Conclusion

Nexus is thus a complex model, which intends to be as complete as possible to address the issue of land use allocation. Our focus in this report is the way to deal with the demand side in Nexus Land Use. However, we don't deal with aspects relative to trade (market organization, international trade, tariffs, subsidies, agricultural policies etc.). We only intend to study the choice functions of agricultural landowners. We will focus on the technical and economic modeling of supply. The precise question we address here is how to represent supply so that it provides realistic results in the long term.

5. Problematic and available data

Democracy is the worst form of government, except for all those other forms that have been tried from time to time
from a House of Commons speech on Nov. 11, 1947
Churchill, 1874-1965

5.1. Cost data: the GTAP[15] database

Like many economic models in general equilibrium, Nexus is based on GTAP. The GTAP version 6 database represents global production and trade for 89 country/regions, 59 commodities and 5 primary factors. The data characterize intermediate demand and bilateral trade in 2001, including tax rates on imports and exports and other indirect taxes.

The advantage of GTAP is that it is a very complete input-ouptut database. But it is very inaccurate in terms of data itself. GTAP is like democracy was for Churchill, as he expresses it in his famous dictum: "Democracy is the worst form of government, except for all those other forms that have been tried from time to time." (House of Commons speech on Nov. 11, 1947).

GTAP database is organized by type of industry. As it is very hard to reorganize GTAP industry types, Nexus follows exactly the same organization as in GTAP, and there has been no attempt to work by farm type for this same reason. Anyway, there is, to our knowledge, no existing global dataset enabling a study of farm types at a global scale. However there is at least a European dataset (the RICA[16]), but access to this set of data has already been refused for confidentiality reasons.

As can be easily observed, GTAP contains a lot of data. As a consequence of this, Nexus is very difficult to initialize. A way to solve this complexity problem would be to reaggregate the data, just like in other models where agriculture consists only of a few categories, (3 crop categories in FARM, see p.39) or even just one (1 crop category in IMAGE, see p.41). It is worth noting that the current GTAP disaggregation is not always the most pertinent for the use Nexus makes of it. Indeed, it isn't based on agronomic data, but rather it was chosen to facilitate accountancy, or by pooling products with the same kind of final use. For instance, it is not very compatible with land use modeling to have milk production data separated from meat production data.

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[15] GTAP: Global Trade Analysis Project
[16] RICA: Réseau d'Information Comptable Agricoles, service provided by the Department of Agriculture and Rural Development, European Commission

5.2. Land Use data

The *FAO*[17] aggregates national declarations about land use. However, this data is not convenient to download and thus exploit. What is more, this data is not spatialized but rather averaged at the national level, even for big countries such as Russia, Brazil, Canada, and the United States. The FAO data are often used in research, however, less because of their quality than because of their convenience. The FAO does not gather data independently for the FAO's Production Yearbooks; it rather collates numbers reported by member states. Hence the data quality varies greatly by country, and country size determines the scale at which the (national-level) data are presented (Meyer and Turner 1992).

There are also *regional databases* such as Eurostat for Europe, and NASS[18] for the United States, but finding all regional databases available worldwide for a global study is a very long work which cannot be undertaken in the context of our study.

Finally, global land cover patterns are accessible via *satellite imagery*. We were able to identify a few grid point databases and maps, but our work should be pursued in order to identify the maps representing crops that are useful to Nexus, and to associate to each of the crops the corresponding yield. Such mapping work has already been done by Ramankutty and Foley (1998) and Heistermann et al. (2006b). The latter developed an allocation methodology which combines land cover characterization by remote sensing with census data on national and sub national levels. The resulting crop distribution pattern provides a plausible and consistent representation of crop geography and is consistent with existing expert knowledge and other available data and information sources.

The available databases and maps produce the following information about land use:

Croplands and *pastures* have become one of the largest terrestrial biomes on the planet, rivalling forest cover in extent and occupying about 40 % of the land surface (Foley et al. 2005).

Cultivated land is defined as areas that are regularly used to grow domesticated plants. They range from long-fallow, land-rotational systems to permanent, multi-cropping systems. Estimates of current cultivated land go from 14.75 to 15 million km^2. The area suitable for rain fed agriculture is estimated by some to be about 18.74 million km^2. The six most widely grown crops in the world are wheat, rice, wheat, soybeans, barley and sorghum. Production of these crops accounts for over 40% of global cropland area, 55% of non-meat calories and over 70% of animal feed (Lobell and Field 2007).

There has been no standardization of definitions related to *forest* yet, and it is thus found under a variety of meanings.

- Closed as opposed to open woodland
- Inclusion of savanna and land used in fallow agriculture
- Exclusion of tree plantation.

According to the FAO, the planet has more than 10% of canopy cover.

[17] FAO: Food and Agriculture Organization

[18] NASS: National Agricultural Statistics Service, part of the United States Department of Agriculture (USDA)

Grassland and *pasture* can be defined as land having a ground story of vegetation cover in which grasses are the dominant life form. The FAO estimates them to cover 67.88 million km^2 (Meyer and Turner 1992).

Of course, a very important type of land use for humanity is urbanization. Although it is important in terms of economic activity and demography, Grübler (1994) reminds that it occupies less than 2% of the earth's land surface. He concludes that changes in the area of urban land per se, therefore, do not appear to be central to land-cover change. However Folke et al. (1991) argue that, in reality, urbanization affects land change elsewhere through the transformation of urban-rural linkages. For example, urban inhabitants within the Baltic Sea drainage depend on forest, agriculture, wetland, lake and marine systems that constitute an area about 1000 times larger than the urban area. As we can thus see, the importance of urban areas is subject to controversy.

In the context of an “engineer-type” modeling, we will not only have to know what kinds of crops are grown in which conditions in the present. We will also need to know how crops will be able to adapt to new regions or new conditions. Hence we need maps of the present climate, the expected future climate, of physical and chemical features of the soil, as well as of agricultural practices.

5.3. Data on agricultural practices

To our knowledge, there exists no map of agricultural practices. National or regional databases such as Eurostat certainly give information on agricultural inputs, for instance national average fertilizer quantity per hectare, number of tractors per farmer, etc. However this kind of information is not always available for all countries, and above all, it doesn’t cover all aspects of technical itineraries. The FAO also provides such information for all countries worldwide, but it is not spatialized.

There have been recent attempts to recreate such data. For instance, Heistermann and Stehfest (2006) developed a scheme to calculate global planting dates on a global 30 arc minutes grid, based on average monthly climate. Heistermann (2006) also developed a model of the spatio-temporal distribution of irrigated areas, in order to address the role of irrigation in agricultural land management and intensification.

5.4. Data on climate

Two main databases are available for information on the climate.

The LSCE[19] , which collaborates with the CIRED, is able to provide data about the present climate and projections of the climate in 100 years for the whole world.

The CRU[20] on the other hand provides freely available monthly data for mean temperature, precipitation, number of wet days, and sunshine hours. This information is gridded at 0.5 degree resolution for 1901-2000.

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[19] LSCE : Laboratoire des Sciences du Climat et de l’Environnement

5.5. Data on soil features

Soil quality, as well as yield potential, is an elusive concept that is difficult to define and measure. Definitions of soil quality in recent literature stress the capacity to support biological productivity, maintain environmental quality, and promote plant and animal health (Oldeman 1994). Let alone this broad definition, it can be argued that the specific soil properties that support crop productivity, such as nutrient reserves, water holding capacity, and favorable structure for root growth, are the very same features that contribute to the environmental services that soils furnishes (Cassman 1999).

Soil is characterized by physical, chemical and biological attributes (Cassman 1999).

- Physical attributes of the soil comprise: the size and continuity of pores, the aggregate stability, impedance, and texture, which determine soil structure.
- Chemical properties comprise: organic matter content and composition, nutrient stocks and availability, mineralogy, and the amount of elements and compounds that are deleterious to plant growth.
- Biological attributes are for instance: the quantity, activity, and diversity of microbial biomass and soil fauna.

Soil degradation can be defined as a reduction in soil quality as a result of human activities. The four major types of soil degradation are water erosion, wind erosion, chemical degradation (salinization, acidification, pollution etc.) and deterioration of physical properties (ibid.). Soil degradation is a major threat to food security because it diminishes potential yields. This kind of degradation can be remedied, but the cost can be prohibitive as degradation becomes severe. Prevention is the key.

Some maps exist about soil degradation, but none of them was found to be very satisfying. Some quantitative data also exist. For instance, Doran et al. (1994) estimate that the total area with some form of soil degradation is about 2000 million ha. About 60% of this degraded soil is found in dryland regions poorly suited for intensive agriculture. Inappropriate farming methods, deforestation, and overgrazing were identified as the primary causes. It is estimated that 555 million ha have undergone various forms of chemical and physical degradation not directly associated with erosion (ibid.). The FAO estimates that 5.44 million km^2 of rainfed cultivated land have been lost worldwide to degradation. Another study estimates 20 million km^2 of former crop land have been irreversibly lost due to degrading uses and to permanent cover land (Meyer and Turner 1992).

5.6. Data on water

5.6.1. What kind of water should we consider in land use studies?

Different water quantities can be distinguished in relation to agriculture, that is, there are different ways to take water into consideration.

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[20] CRU: Climate Research Unit

5.6.1.1. Physical data:

One can look at climatic data (see 5.4) such as precipitation, to have an idea about water availability for plants. Climatic data can be supplemented by physical or geographic data (see 5.5) about surface water and groundwater quantities. Such data gives an indication of how much water is available on the whole for any activity it might be used for.

However, concerning rainfall, part of the rain water percolates below the root zone of the plants and part of the rain water flows away over the soil surface as run-off. This deep percolation water and run-off water cannot be used by the plants. In other words, part of the rainfall is not effective. The remaining part is stored in the root zone where it can be used by the plants, it is the effective rainfall. The factors which influence which part of rainfall is effective and which part is not include the climate, the soil texture, the soil structure and the depth of the root zone. If the rainfall is high, a relatively large part of the water is lost through deep percolation and run-off. In many countries, formulas have been developed locally to determine the effective precipitation. Such formulae take into account factors like rainfall reliability, topography, prevailing soil type etc. There also exist some rough estimates of the effective rainfall based on the actual rainfall. (FAO)

5.6.1.2. Crop water requirements:

Water can be taken into account through the study of crop water requirements. The crop requirements are driven by the combination of two separate processes, whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration. This phenomenon is referred to as crop evapotranspiration (ET_c). The crop water need mainly depends on the climate, the crop type, and the growth stage.

One crop grown in different climatic zones will have different water needs. It is therefore useful to take a certain standard crop or reference crop and determine how much water this crop needs per day in the various climatic regions. As a standard crop, or reference crop, grass has been chosen. The daily water need of the standard grass crop is also called “reference crop evapotranspiration” or ET_o.

The influence of the crop type on the crop water need is important in two ways:

- The crop type has an influence of the daily water needs of a fully grown crop (i.e. the daily peak water need)
- The crop type has an influence on the duration of the total growing season of the crop

The growth stage of the crop has an influence on crop water needs, because when the plants are very small, the evaporation from the soil and plant surface will be more important than the transpiration. On the other hand, when the plants are fully grown the transpiration is more important than the evaporation.

Direct calculation of crop evapotranspiration (ET_c) implies either measures of mass transfers or energy balance of a cropped surface, or studies of soil water balance, or the derivation of ET_c from meteorological and crop data by means of the Penman-Monteith equation[21].

When direct calculation is not possible, which is the case in modeling of a large number of crops in different climatic and geographic conditions, the "crop coefficient approach" can be used to calculate the crop evapotranspiration under standard conditions (ET_c). The standard conditions refer to crops grown in large fields under excellent agronomic and soil water conditions. The crop evapotranspiration differs from the reference evapotranspiration as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ET_o by K_c:

$$ET_c = ET_o \times K_c$$

Most of the effects of the various weather conditions are incorporated into the ET_o estimate. Therefore, K_c varies predominantly with the specific crop characteristics. It represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass: crop height, albedo of the crop-soil surface, canopy resistance, evaporation from soil. Consequently, different crops will have different K_c coefficients. What is more, the changing characteristics of the crop over the growing season also affect the K_c coefficient. This enables the transfer of standard values for K_c between locations and between climates. The reference ET_o is defined and calculated using the FAO Penman-Monteith equation. Standard values for K_c are available on the FAO website for many different crops.

Such processed data gives information about a theoretical water quantity that should be brought to the plant in order to meet some yield expectations. It doesn't give any indication on the water quantity which is actually brought to the plant.

5.6.1.3. Irrigation data:

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[21] In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaportaion from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This combination method was further developed by researchers and extended to cropped surfaces by introducing resistance factors. The Penman-Monteith form of the so-called combination equation is :

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where R_n is the net radiation, G is the soil heat flux, (e_s-e_a) is the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ is the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the surface and aerodynamic resistances. (FAO)

Finally, water can be represented by data about irrigation. This data can take the form of irrigation areas, that is, areas that are already covered with an irrigation network, whether it works or not, or areas that are covered with an irrigation network that is actually used. Irrigation can also be represented by irrigation water quantities. This kind of data is likely to give a better idea of the water that is actually used for plant cultivation under irrigation. It is also likely to give an idea of the pressure of agriculture over water resources, because irrigation is the way to draw water from the environment to supply agricultural systems. Such data can be found on various databases that we detail further.

5.6.2. Data problems constrain the choice of the study object "water"

Meteorological data provide useful data about precipitations at the gridpoint level (geospatialized maps) or aggregated at national levels.

However it proves very difficult to find data about the quantity of water consumed for irrigation per crop per country for several reasons:

(1) There exists no standard accounting system in irrigation networks

(2) It is difficult to distinguish between the quantity of water brought to the irrigation canal and the quantity of water which is actually consumed, for there are very variable losses in the whole system depending on the technology, the type of service and local practices. As a consequence of these both facts, the databases provide assessments of the evaporated water depending on agronomic parameters, and these assessments are thus in general very different from the reality.

Different definitions of water resources exist, depending on the database considered, which makes it hard to get an idea of the accuracy of such or such data (see

(3) Table 1).

The available quantitative data we found on global water use and availability comes from 3 main different sources: (1) IRENA/Eurostat, (2) Aquastat (FAO), and (3) OECD.

(1) IRENA's data on water comes from Eurostat. It consists in irrigated areas per crop type per country, but the sum of irrigated areas is often different from the data of the total irrigated area. Much data is missing. There is also data about the quantity of water used per country per year.

(2) Aquastat's data (FAO) was collected from Aquastat polls in each country. When the country statistics weren't available, the data was estimated (e.g. by supposing that the relative change in water extraction is equal to the relative change in irrigated land, which is available in the same database). Aquastat also provide data about irrigated areas per country per year, and about water quantities extracted for irrigation and for agriculture per country per year. The data about irrigated areas is full of gaps.

(3) The OECD’s data comes from the OECD Environmental Data Compendium 2004; OECD 2nd Agri-Environmental Indicators Questionnaire, 2004. They are very inconvenient to deal with because they need to be extracted country by country, and thus they haven’t been used. They seem to be very similar to that of Eurostat because the OECD and Eurostat use a common questionnaire.

Heistermann (2006) report the existence of a digital global map of irrigated areas. However on the whole it appears that there is very little reliable, complete and easily available data on water used for irrigation.

Water withdrawal
Water removed from any source, either permanently or temporarily. Mine water and drainage water are included. Water abstractions from groundwater resources in any given time period are defined as the difference between the total amount of water withdrawn from aquifers and the total amount charged artificially or injected into aquifers. Water abstractions from precipitation (e.g. rain water collected for use) should be included under abstractions from surface water. The amounts of water artificially charged or injected are attributed to abstractions from that water resource from which they were originally withdrawn. Water used for hydroelectricity generation is an in-situ use and should be excluded.
Irrigation use
Artificial application of water on lands to assist in the growing of crops and pastures.
Irrigation water
Water which is applied to soils in order to increase their moisture content and to provide for normal plant growth.
Irrigable area
This term is used in the EUROSTAT statistics with the following meaning: The maximum area which could be irrigated in the reference year using the equipment and the quantity of water normally available on the holding. The meaning is therefore similar to the term area equipped for irrigation used by the FAO. However, the total irrigable area may differ from the sum of the areas provided with irrigation equipment since the equipment may be mobile and therefore utilisable on several fields in the course of a harvest year; capacity may also be restricted by the quantity of water available or by the period within which mobility is possible.
Irrigated area
In general this term refers to the area equipped for irrigation. EUROSTAT however uses this term in the following meaning: Area of crops which have actually been irrigated at least once during the 12 months prior to the survey date. The definition used by EUROSTAT is therefore similar to the area actually irrigated as used by the FAO.

Table 1. Definitions related to agricultural water use (Eurostat, FAO)

5.7. Data on livestock

The FAO provides data about number of live animals; data about primary animal products in average carcass weight, in numbers of slaughtered animals, and in tons of primary product; data about processed livestock and feed.

We also used INRA tables about animal feed requirements in terms of energy, protein, minerals, and feed digestibility; and about transformation coefficients of animal feed (Jarrige 1988).

5.8. Data on energy

The NRData datasets provides information on:

- The final energy consumption of the agricultural sector for all countries. Energy consumption is divided into a few categories, the most important (i.e. the most significant quantities) being oil, electricity, gas and coal. We used quantities in tep between 1995 and 2005 for European countries.
- Energy prices for all energies. We used prices in current US$/tep for oil, electricity, gas and coal. We assumed that prices for agriculture were the same as prices for industries. We used prices for residential areas when they were the only ones available. For oil prices we used prices of light fuel.

This database provides information on energy consumption by the whole agricultural sector. We assumed that the share of each type of energy in the total energy consumption was constant throughout the different sectors of agriculture in a country.

When adding up energy costs for agriculture from NRDatabase on the one hand, and from GTAP on the second hand, we found that total costs are very different from one base to another. These differences range from 3% (Germany) to more than 70% (Greece). The mean difference is 26.5%.

5.9. Data on Greenhouse Gases

A widely accepted methodology to calculate greenhouse gas emission coefficients by agricultural production and production technique was elaborated by the IPCC (2006). However it proved very difficult to use for calculations of emissions based on available data on land use and technical itineraries. Indeed, as mentioned earlier in this report, such data is either too scarce or too imprecise.

As a consequence, we took our data on total greenhouse gas emissions directly from the European Environmental Agency (EEA). The data was originally calculated by countries following the IPCC recommendations, and sent to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism (EU Member States). Data compiled and held by ETC/ACC (European Topic Center on Air and Climate Change – EEA center of thematic expertise) are annual emissions of CO2, CO2-removals, CH4, N2O, HFC-A, HFC-P, PFC-A, PFC-P, SF6-A, SF6-P from individual countries. Sectoral data (IPCC classification) is provided for the different source categories: Energy, Industrial Processes, Solvent and Other Product Use, Agriculture, Land-Use Change and Forestry, Waste, Other, CO2 emissions from Biomass, International bunkers and Multilateral Operations. We focused on the Energy (for agriculture) and Agriculture categories, as well as on annual emissions of CO2, CH4, and N2O only, for they are the main greenhouse gases emitted by agriculture.

We haven't taken into consideration all categories, in order to keep the most representative ones, and to make them correspond to the Nexus land use model categories. The sub categories taken into consideration are the following:

- Dairy Cattle (1)
- Non Dairy Cattle (2)
- Sheep + Goats (3)
- Swine (4)
- Poultry (5)
- Rice cultivation (6)
- Direct emissions (7)
- Indirect emissions (8)
- Animal production (9)
- Field burning of agricultural residues (10)
- Energy Agriculture/forestry/fisheries (11)

5.9.1. Explanations of a few categories

Categories 7 to 9:

Three sources of N_2O are distinguished in the most recent IPCC methodology (2006): (i) direct emissions from agricultural soils, (ii) emissions from animal production, and (iii) N_2O emissions indirectly induced by agricultural activities. These three categories correspond to the following processes: N_2O may be emitted directly to the atmosphere (i) in agricultural fields, (ii) animal confinements or pastoral systems or (iii) be transported from agricultural systems into ground and surface waters through surface runoff. There are two potential sources of nitrous oxide in animal production (i) wastes from confined animals and (ii) dung and urine deposited on the soil by grazing animals. Emissions induced by use of manure N as fertilizer applied to agricultural fields are considered direct nitrous oxide emissions from agricultural fields.

Missing categories:

4 categories haven't been taken into account: anaerobic lagoons, liquid systems, solid storage and dry lots, other AWMS (Agricultural Waste Management System). These categories correspond to different types of animal waste/ manure management systems. Emission data is provided for these categories for N_2O only, whereas CH_4 emissions from manure management are disaggregated by animal categories and not by manure management systems. The problem with disaggregating by manure management system is the reference data. And indeed, we don't know what proportion of manure is managed in such or such way. Therefore we can't relate the GHG emissions to a certain quantity of manure for example, or to any other variable we could manipulate easily in an economic model. To address this problem we could look more precisely into emission factors for animal waste per animal waste management system, detailed in the 1996 IPCC methodology. However this reference is old and certainly out of date.

5.10. Data on pollution

Progress has been made on developing common methodologies to measure the environmental performance through the construction of environmental indicators, which are simplified statements meant to capture the key factors involved in the complex relationships between agriculture and the environment (Arsalane 2006).

OECD has thus produced a set of agri-environmental indicators and put them to use. What is more, within the European Union, five services have been particularly involved in the production of indicators grouped under the name IRENA (Indicator Reporting on the Integration of Environmental Concerns into Agriculture Policy). Five environmental subject areas were highlighted representing various topics of agri-environmental policy: (1) agricultural nutrient loading, (2) GHG emission, (3) pesticide use, (4) species diversity, (5) landscape.

Both of these sets of indicators have been thoroughly studied in the context of our work on land use modeling, and were found to be very incomplete, and not spatialized. What is more, they are not adapted to the GTAP crop categories that are used in Nexus Land Use model. That is the reason why we decided to develop our own set of indicators, first for Europe in the context of our work for the MATISSE project (see 7, p.99). This set of indicators is to be extended to the 87 GTAP countries.

6. Improving the supply side of Nexus model

6.1. Objectives

We know that the present agricultural system is able to feed the world population, although a bad distribution of the resources is responsible for famines. We know the world population will keep increasing and will get richer, so the world population will consume more and more resources and be increasingly more land intensive. Moreover, the widely recognized global warming, created by our carbon intensive use of fossil resources, is impacting the Earth.

The model Nexus Land Use aims at giving an idea of the difficulty of feeding the next generations, of the sustainability of future agriculture, an of its environmental cost. As a prospective exercise, we want to be able to test different hypotheses in terms of climate change, agricultural technology improvement and agro-carburant policies scenarios.

Nexus land-use must be designed to answer the best those issues.

As we have seen previously, our main constraints are:

- Data is scarce, often unreliable, and imprecise
- Simplicity in modeling is required, otherwise, the program of the model will take a long time to provide results, which will be difficult to understand

We shall thus present here a few thoughts about the agriculture production part of Nexus land use. These are possible improvement paths for Nexus. As was reminded in the model review, two kinds of approaches are possible in the modeling process: a statistical and a technical approach.

The statistical approach is easy to adopt when data is of acceptable quality. This approach may enable to predict short term events. Yet, it can not be a solution to analyze long term processes where some major changes may happen (global warming, stabilization of maximum yield, etc.).

To fulfill Nexus' objective, we will prefer a technical or an economic and technical modeling method, which will take into account physical, biological, technical, economic mechanisms in a more or less detailed fashion. To be able to do so, we need to know what a yield and a production surface depend on. Two main questions have to be answered, and they are not totally independent:

- How shall we represent yield increase?
- What is the relevant technical precision level?

6.2. Question of time and technology: How will average crop yields increase?

6.2.1. The issue of carrying capacity

The issue of the world's carrying capacity, that is, the maximum number of individuals that the world can support without detrimental effects, is very classical and numerous research works have tried to address it. The underlying question is the following: "is the world approaching carrying capacity in agriculture?" (Harris and Kennedy 1999).

A number of studies (e.g. studies by the Worldwatch Institute) have suggested that the answer to this question is yes, that is, that we are close to facing some very serious problems of food security and environmental catastrophes. However others, for instance the World Bank and the Council for Agricultural Science and Technology (CAST), are generally optimistic that meeting future food needs will be possible and even increasingly easy. FAO and IFPRI[22] models assume a carrying capacity of 12 billion people. The middle position suggests that predictions of unprecedented food security crises are excessively simplistic, but that technological optimism understates the importance of ecological stresses.

The wide divergence in projections of agriculture futures is mainly due to the yield increase potential hypothesis. It can be traced to different methodological perspectives of ecological and neoclassical economics.

[22] IFPRI: the International Food Policy Research Institute

6.2.2. The yield increase potential

Neoclassical models are oriented toward incremental growth without inherent limits. It is the method employed by the contributors in the IFPRI study previously mentioned. This method consists in basing future agricultural production estimates on a projected rate of yield growth. The yield growth is presumed to be a result of continuing technological improvement and investment in agriculture. Historical growth rates are used as a baseline for estimating future growth rates. The result is that these models generally display exponential growth in yields over time. This is a crucial factor from which their mostly optimistic conclusions about future supply/demand are derived (Harris and Kennedy 1999).

For instance, in the model AgLU (see p.34), Sands and Leimbach (2003) simulate increases in AgLU crop yield in a range of 0.0% to 1.5% per year, with the model running in fifteen-year time step. A crop yield growth of 1.5% per year leads to an exponential growth over time.

Ecological models on the other hand start from the premise that there are obvious inherent limits to capture and use of solar energy and planetary resources. And indeed, first, the solar energy is a defined and measurable value. Second, the photosynthesis capacity is inherent to a plant and seems to be a very difficult factor to improve (plant selection did not manage to improve photosynthetic capacity, but rather stress resistance). That is why the use of a logistic path for crop yields with some upper limit is more logical from this point of view. In its early stages, a logistic growth path closely resembles an exponential path. But as the upper limit starts to exert more influence, the growth rate slows, passes through an inflection point, and ultimately approaches zero as the carrying capacity is approached. Of course, the seriousness of an error like taking the exponential path instead of the logistic one would depend on the upper limit in question.

Harris and Kennedy (1999) mention a study using a logistic projection for maize yields. In this case, the upper limit is 21 metric tons per ha, which is close to the theoretical photosynthetic limit on yields in the USA today (estimated to be 3 times the actual average yields). However, the theoretical genetic potentials of plant physiology are commonly constrained by unfavorable physicochemical environment. What is more, global soils are generally subject to more stresses and productivity constraints than the major US crop-growing area. This provides strong evidence for a yield limit significantly lower than the theoretical potential. Consequently, the logistic patterns which fill observed trends generally indicate a potential for doubling, rather than tripling, yields over the next 50 years (Harris and Kennedy 1999).

If we consider a crop yield logistic curve, it could be interesting to consider that different nations may be in different regions of a logistic growth curve (developing nation are 15 years behind developed nation in achieving a particular yield) (Harris and Kennedy 1999). It is possible to add complexity to yields in Nexus, if we define the maximum yield as a function of the latitude. So the yield growth capacity of African countries would be higher than the European, and the former countries would be considered as being in the lower regions of the logistic curve. This could be justified by the existence of different stresses (water, parasites, soils quality) and by the low level of intensification in African countries.

6.3. What is the correct crop production function?

As it was already said, crop yields depend on many parameters. Some of them could be considered as characteristic of an area: soil quality, weather, slope, etc. Other parameters depend on the country technicity level: mechanization, crop varieties, etc., or policies: incentives, taxes, etc.

A yield is a consequence of the complex interaction of plenty of factors. These factors can be categorized in few main types:

- Related to local and constant conditions: soils quality, global weather, soil slope, etc.
- Related to the plant: type of plant (rice, wheat, etc.) and plant quality (resistance to drought, etc.)
- Related to agricultural practices: date of seeding, quantity and time of inputs used, irrigation, soil work (tillage, etc.)
- Related to weather: average and extreme temperatures, seasons, precipitations, etc.
- Related to some random events: parasite attacks, plant illnesses, etc.

All those factors are much too precise for our needs. Since we are working at the world level, we can aggregate our data. By aggregating we will occult very local effects such as random events.

The parameters we are interested in here are directly related to the farmer's choices. From one year to another, to adapt to the market tendency, farmer can change their production choices and techniques pretty quickly. For example they can modify their input use levels (especially nitrogen), irrigation practices, or pesticide use level.

6.3.1. Continuous model

6.3.1.1. Considering only one parameter

If we consider, only one of the parameters mentioned above (input level, irrigation, pesticide use etc.), finding a crop response is not very difficult. Usual models show a decreasing effect of the input efficiency. Godard (2005) reports that the INRA uses logistic curves to describe crop yield response. Other experimental data show a positive but decreasing effect of the input on crop yield, then a plateau (saturation) and a negative effect (toxicity).

Of course, the crop response also depends on local parameters (soil quality, weather, etc.) and on technicity parameters (especially how and when the input was use). But those parameters can be considered as the ones precisely defining the plateau (maximum yield possible).

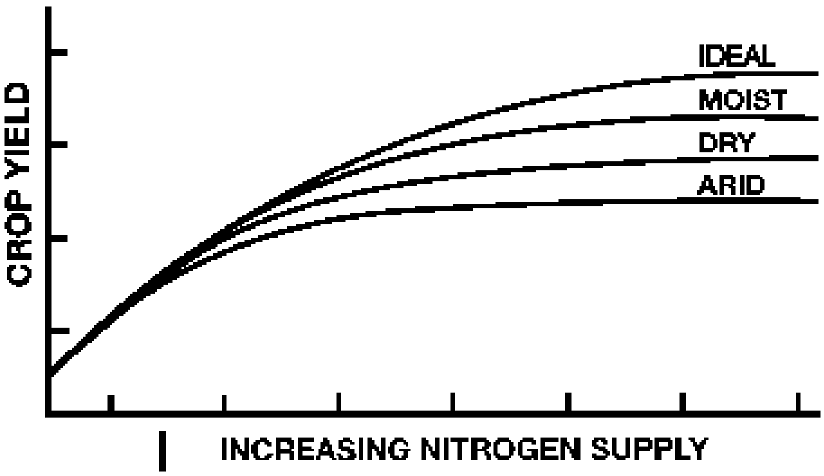


Figure 14. Yield response of cereals to nitrogen supply under different moisture conditions

For instance in the figure above, increased nitrogen supply increases the crop yield at decreasing rate, and the plateau is defined by the moisture conditions. The moisture condition is thus here the limiting factor.

The crop water stress response is more difficult to assess. Some studies seem to show that the same function types should be used. Yet, for water, more than for input, timing is important as the water doesn't stay in the soil as long as N inputs.

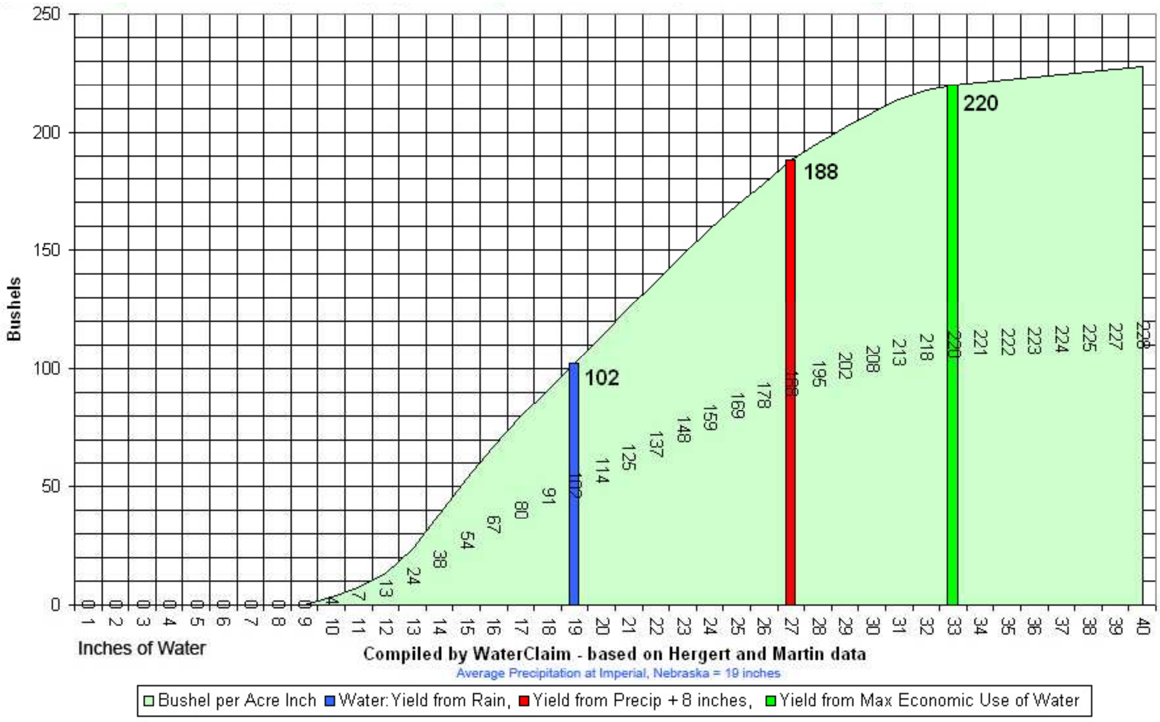


Figure 15. Corn response to water (www.waterclaim.org)

Another major problem is that irrigation potential is clearly limited by surface water scarcity. By contrast, in the case of N input, we can expect farmers to use the quantity that will maximize its benefits. However this is totally impossible to do with irrigation, as irrigation systems are all but flexible. One can assume that the farmers will irrigate up to the full irrigation capacity, because the variable costs (cost of water) are negligible compared to the fixed costs (cost of the infrastructure). And indeed, according to experts, there are very few countries where farmers pay water. The only cost is irrigation infrastructure (and sometimes the cost of pumping). So the economic choice of the farmer is different from that for other inputs. The question is not how much irrigation costs, but rather what the difference is between “no-irrigation associated to no cost”, and “no-water stress associated to the fixed costs of the irrigation system”. In other terms, are the costs of water stress yield deficits compensated by the fixed costs of an irrigation system? The answer depends on the importance of the water stress, the crop price and on the cost of the irrigation system (increasing with the distance to the source). So water can not really be considered in a continuous model.

At the valley level, another question is very important: what is the maximum water quantity the farmer can use?

6.3.1.2. Considering more than one parameter

As soon as we want to consider more than one parameter at the time, the problem starts to be more difficult. Using the functional forms of the function described above (for instance quadratic, three-halves or square root polynomial functions) creates a huge discrepancy: substitution becomes possible. For instance, with such functions it would be possible to substitute water by nitrogen (Grimm et al. 1987). Some more interesting polynomial functions considering interactions between inputs may be used (Finger and Schmid 2007), but they don’t fit so well with reality (Grimm et al. 2007). Furthermore, the number of interactions between parameters is increasing tremendously with the number of parameters introduced. It might thus be difficult to extend the model to three or four parameters.

The Von Liebig Model seems to be more consistent. This century-old model is considering the limiting nutrient principle for all macro-nutriments including water. In its formulation, it assumes a linear crop response to the limiting nutrient until a maximum plateau is reached and another factor then becomes limiting (Grimm et al. 1987).

Obvious as it might seem, it is very interesting from a theoretical point of view, but it can be more difficult to use. All crop functions described in the Von Liebig study come from statistics done on very local data. The maximum production thus depends on the local geophysical environment. Such models are consequently difficult to extend to other geographical areas, and to parameterize. The question is indeed, if we know the average yield, the irrigation level and N input uses in a country, can we guess the production function?

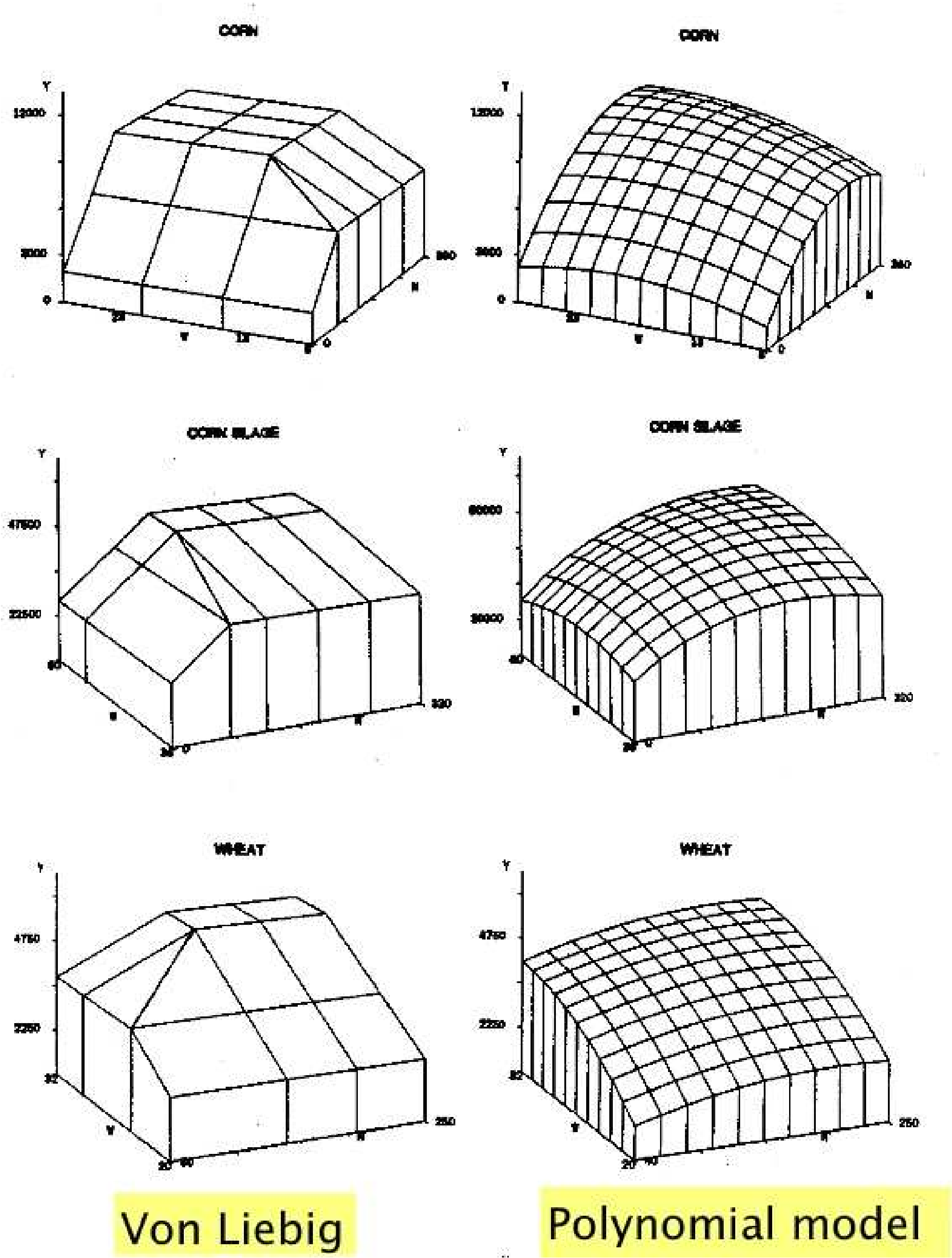


Figure 16. Von Liebig and polynomial model (Grimm et al. 1987)

6.3.2. The discontinuous solution

A discontinuous solution is far more easy to use. This is typically the kind of solution used in the case of irrigation.

6.3.2.1. … only consists in adding crop types

Within a country, instead of considering 8 crop types, 16 (8x2) crops types can be considered: 8 without irrigation, and the same 8 with irrigation. In this framework, farmers won't choose the most profitable crop production between 8 but between 16, while demand will still be driving production of only 8 crop types.

Some easy constraints on water use intensity can be added, such as, for instance, a maximum total irrigated surface per country (e.g. FASOM see p.36).

6.3.2.2. .. But it allows to consider complex interactions

However, a new kind of tool has been developed and seems very attractive. We are talking here about models of crop physiology. Such models have long been considered as too complex.

There are different models simulating crop growth: STICS (Brisson 1998), Daycent (Stehfest et al. 2005). They were created with different objectives: to understand how yields are formed, to understand erosion phenomenon and soil pollution, etc. In the end, they all model the continuum soil-plant-atmosphere in a more or less precise fashion. Their accuracy has often been confronted to experimental data. The most precise models take into account very numerous and precise input parameters: geophysical (description of soil layers, of the daily evolutions of temperature and rainfall during the plant development cycle, etc.), technical itineraries (soil manipulation type and date; type, quantity and date of use of input, phyto-sanitary products; irrigation; intercropping and multiple cropping patterns, etc.), all this being dependent of the type and variety of plant considered. The output variables are all the same very complete, and concern production quantity, soil final state and emitted pollutants.

6.3.2.3. STICS, the French model by the INRA

STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) models the ways cultures function with a daily time step. The input variables are relative to climate, soil, and cultural systems. The output variables are relative to production (quantity and quality), to the environment and to the evolution of soil features under the effects of the culture. STICS was designed as a tool for operational simulation in agricultural conditions. Its main objective is to simulate the consequences of the variations of the environment and the cultural system on the production of an agricultural plot and on the environment. It was also designed as a working tool, and a tool for collaboration and of knowledge transfer towards other related scientific fields (Brisson 1998).

STICS' advantages are the following:

- Its genericity: it is indeed adaptable to different varied crops (wheat, maize, soybean, sorghum, linseed, prairies, tomatoes, beets, sunflowers, peas, barley, bananas, sugarcane, carrots, lettuce etc.).
- Its robustness: it is able to simulate various pedo-climatic conditions without generating any important bias, but sometimes to the expense of local precision.
- The easy access to parameters and input variables.
- Its conceptual modularity: it is possible to add new modules (e.g. volatilization of ammoniac, symbiotic fixation of nitrogen, vegetal mulch, stony soils, multiple organic residues, etc.). This modularity aims at facilitating ulterior evolutions of the model.
- The context of internal and external communication that STICS generates is used as a basis for the model's evolution, which is concretized by the successive versions of the model's software.

The superior limit of the system is the atmosphere, which is characterized by standard climatic variables (radiation, minimal and maximum temperatures, rainfall, reference evapotranspiration or wind and humidity), and the inferior limit corresponds to the interface ground / underground.

The culture is considered in a global fashion by its biomass over ground, its nitrogen content, its foliar index, as well as the number, the biomass and the nitrogen content of the harvested organs. Thus, the vegetative organs (leaves, ramifications or talles) are not individualized. The soil is assumed to be a succession of horizontal layers, each of them being characterized by its water content, and its mineral and organic nitrogen content. The interactions between the soil and the culture are made by the roots, which are defined in the model by a distribution of root density in the different soil layers.

STICS simulates the carbon balance, the water balance and the nitrogen balance of the system, and enables calculations of agricultural variables (yields, input consumptions), as wall as environmental variables (water and nitrogen losses) in different agricultural situations. The possible existence of stresses (water or nitrogen deficits or excess, excessively low or high temperatures) is taken into account through indexes which can quantify the reduction in vegetative growth, and that of storage organs. These indexes are calculated in the water, nitrogen or energetic balances.

STICS thus enables to simulate some typical behaviors, to know their impact on yields, but also on the environment (soil quality, quantity of inputs washed out, etc.), with a high precision. Given that farmers take their decisions mainly based on profit maximization (and neglecting externalities), STICS thus enables to have an idea of the impacts of policy changes or changes in market conditions on the evolution of these externalities. It also allows for considerations about changes of soil conditions, which will have, in the short or middle run, an impact on production (e.g. salinization[23]), and which will thus have an impact on future generations' capacity to feed themselves.

[23] Salinization is the accumulation of free salts to such an extent that it leads to degradation of soils and vegetation

6.3.2.4. Are crop simulation models too precise?

This type of agronomic model at the plant level can seem to be too precise compared to what we try to do in Nexus. It is really necessary to use a model of the functioning of the crop, when we want to deal with global problems?

Despite the complexity drawback, such models can be very useful:

- These models enable to take into account many different factors. It is also possible to keep some of these factors fixed and to make only some of them vary. Such models are thus more flexible than the statistic models presented previously.
- These models have been tested by comparison with field data, and are thus more reliable than any other models studied previously.
- STICS (and maybe other such models) is constantly evolving, in order to respond to the new needs of its users or to new problematic
- The precise geophysical data needed by these models are often available. Satellite imagery indeed provides precise data for the whole global surface, it is thus possible to know the slope at any precise point of the globe, there are soil maps etc. Climatic models (developed by the LSCE, the IPSL or the LMD for example) provide meteorological forecasts at every geographical gridpoint.
- STICS comprises data relative to numerous plant types and varieties, which enables to respond to agricultural specificities of different regions.
- If it is impossible to know the precise technical itineraries at every location, it should be possible to define a few important types of technical itineraries.

Thus, for a certain soil, a plant variety and a given weather, it is possible to compare yields produced by different technical itineraries. What is more, this type of model can provide information about the consequences of each technical itinerary on the environment, the soil, and on the following cultures (effect of culture rotations). Thus this type of model enables to model the effects of ultra intensive agriculture, of reasoned agriculture, of precision agriculture and of organic agriculture. It is also possible to measure effects of environmentalist policies etc.

6.4. How should we represent the geophysical environment?

So far we have been dealing with the effect of techniques (associated to more or less unpredictable technical improvement or changes) on crop yields. We have also dealt with the production function at a defined time and how we can model it.

But we have neglected up to now what might be the most important question: the impact of geophysical parameters on crop yield. This parameter is also very difficult to deal with.

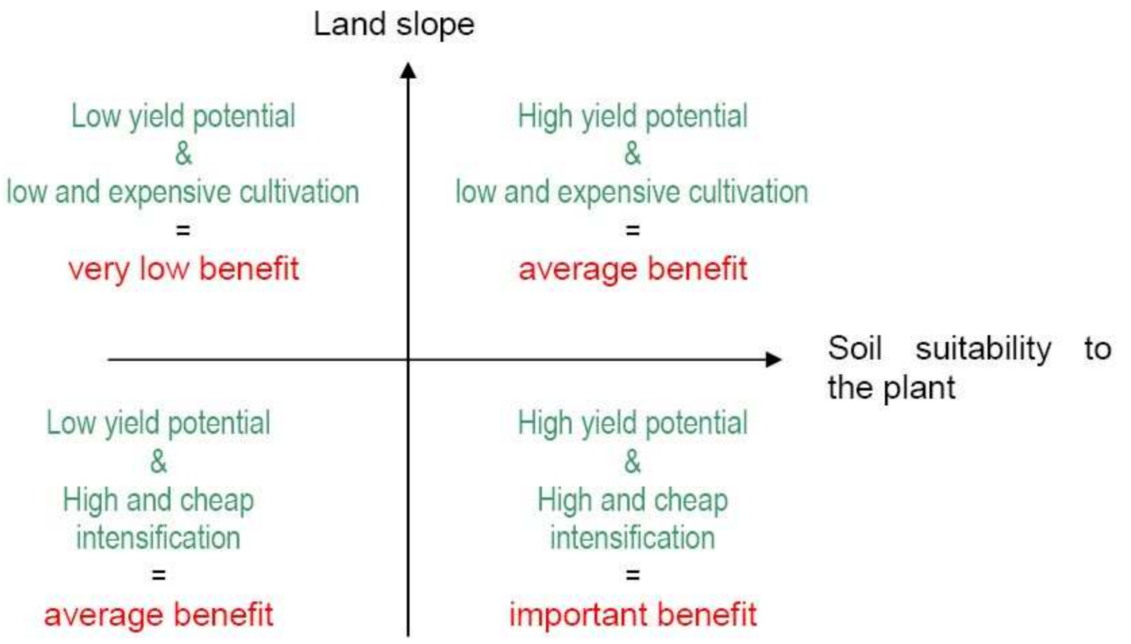
6.4.1. Types of geophysical environment

The geophysical environment, and land quality, can be approached along two dimensions: land suitability to the plant, and land slope.

Land quality is considered as intrinsic in each location (we will see in a second approach that soil quality can be modified by some land uses and agricultural techniques). To put it simply, land will be more or less suitable to different plant varieties, and land slope will enable or prevent the intensification of agricultural practices. To illustrate the role of land slope, a hilly area will increase the risk of erosion, and will prevent mechanization for example. The possibility for agricultural intensification is thus diminished.

This concept of soil quality can be illustrated by the following scheme.

Figure 17. The two dimensions of land quality



Within a country, we can find all of the categories described above, which form of course a continuum. Obviously, the marginal benefits by hectare are different according to the land type, and the plots which are the first to be put under cultivation are those who produce the more benefits. Thus the microeconomic theory fits well with reality. The surfaces for which profit is superior to zero or to a reference benefit (interest rate without risk, or opportunity cost) are put under cultivation. The plots which don’t produce enough benefits stay fallow.

It is worth stressing the fact that we are interested only in the cultivable surfaces. Urban zones are not taken into account in Nexus Land Use, although we know that they occupy the most fertile plots. Non cultivable zones are left out of our study as well.

6.4.2. Use of constant yields

6.4.2.1. Geographical unit

The easiest surface unit that can be considered is the country. This is what Nexus Land Use is doing now.

The FAO gives average yields per ha in 210 countries and territories of the whole world, for many crop types, and for at least the past 10 years. Other databases (Eurostat, National Agricultural Statistics Service, etc.) give regional and sometimes very precise agricultural data. Nexus Land Use uses data produced thanks to the cooperation between the GTAP model team and the SAGE[24] team, which give average yields per country for the 8 crop types used in GTAP data base.

This type of data is interesting. Yields can vary greatly between countries because of incentive policies, history, farm structures, etc., are different.

6.4.2.2. Fixed crop yield, fixed added value/benefit

In this type of approach, there are average crop yields and average added value per crop per ha per country. Hence, an interesting assumption would be to consider crop yield and added value constant per ha and per crop in a country at a defined moment.

Overtime, technical improvement can easily be added using exogenous scenarios. Reference yields can be increased following an exogenous improvement scenario. For instance, in AgLU, crop yields increase yearly by 0, 0.5, or 1 %. The scenarios can also follow a logistic curve on which countries start at different points of the curve. This could be done in order to take into account the fact that the increased yield potential is bigger in low yield countries than in high yield countries. Different maximums can be used for the logistic curves of different countries, in order to take into account how favorable the average local conditions are (for instance, in a country where slopes are important, mechanization is difficult and maximum yield is low).

Technical itinerary are more difficult to add in models adopting the fixed crop yield approach.

We can use the discontinuous method as describe previously. In this method, instead of considering 8 crop types, there can be:

8 crop types x *i irrigation types* x *j levels of N use* x …

To put it differently, technical itineraries have to be divided into well defined categories. The main issues raised by this approach are:

- How should categories be defined, so that they are still relevant in a few decades?
  How can crop yields and associated benefits be derived?

[24] SAGE: Center for Sustainability and the Global Environment

- How so many crop types can be dealt with? (It should be remembered that there are already 87 countries and the model parameterization is a very difficult task to accomplish).

But the main problem is how to integrate a fixed yield model in the economic part of the land use model. Indeed, calibrating a partial equilibrium model with fixed crop yields or fixed added value/benefit is impossible. Since there is no concave function, the solution is either one extreme (complete specialization) or the other (no cultivation).

Other main concerns about using constant yields by country are worth highlighting:

- Climate change impacts different locations in different ways. Its consequences, in terms especially of yields, have to be assessed at the local level rather than at the country level (the sum of local consequences is creating the risk, but within a country some are may win, some other may lose).
- Water constraints are difficult to take into account. They should be thought at the valley scale. Yet, the best we can do here is doubling each crop category in rain-fed crop and irrigated-crop, and limiting the second type in surface.
- Constant yield per ha per crop and per country is an economic mistake, especially for wide countries. For instance, the US prairie lands are more fertile than the Rocky Mountains. The most fertile lands are used first because they are the most valuable. If the model doesn't consider that marginal quality of land is decreasing (and that cost is increasing) with the total surface used, it misses a very important economic phenomenon. This argument should be important enough to exclude the possibility of using this methodology.

6.4.2.3. The continuous method

A continuous method could also be considered. This method implies the definition of a production function, and its parameterization. A continuous production function gives the average crop yield, the input use, the irrigation level, etc. Some experts suggest that this solution is possible for one parameter. But there is no consensual production function used.

Another way to account for yields in a continuous fashion is to consider statistical models. If we have past data (it is the case for some crops in Europe and the US), we can fit yield curves with this data and use them to project a trend.

This approach implies finding historical regional data on yields, and on any other parameter is thought to be influencing yields (climate variables such as rainfall, data about agricultural practices such as mechanization intensity, nitrogen input level, etc.). By linear regression, relationships are found between the chosen explicative variables and the explained variable (yields). The derived trend is then assumed to be valid in a close future, and yields can thus be predicted according to scenarios on weather, or it is possible to recalculate the optimum level of nitrogen use at each time step. Some research was done in this direction (the Ricardian approach by Mendelsohn and al. [1994]). But a few major problems remain:

- There is not enough data to find statistical relationships in every important part of the world or for every parameter might be useful to take into account.
- Statistical data are available within the area where regressions are done. It can be useful to address the short term, but it doesn't really help for long run issues, where

some parameters and the interactions between variables are expected to change dramatically.

6.4.3. The spatial dimension of the model

In every country, land quality for cultivation varies. Land can be either less productive or more difficult to cultivate. In both cases, there is a decreasing added value per ha (or benefit). This is a physical truth and can be used to improve our model. Thus, unequal land production benefits must be taken into account. We can consider either increasing costs, or decreasing yields, or both. In each case, the marginal benefit is decreasing with the total cultivated area. It is worth recalling the fact that the decision of putting new land in culture is based on the expected marginal benefit.

6.4.3.1. How decreasing are crop yields/benefits ?

Available data just gives information on actual average yield/benefit. There is no precise data on the repartition of benefits/crop yields over the cultivated land. And, obviously, there is no data on the potential yields/benefits of none cultivated land.

There are three ways to represent the decrease in the marginal benefit of land.

6.4.3.2. Aggregation of present national data

It is possible to aggregate national or even international data on yields and surfaces and build a distribution function. Indeed, from a set of data and statistical analyses meant to find the appropriate function fitting with the data, a production function can be derived.

For example, the yield distribution curve drawn further (see Figure 18. Graph of wheat yield distribution in GTAP countries was obtained by cumulating hectares of surfaces under wheat cultivation in the 87 GTAP countries. The first hectares to be cultivated are those with the highest yields, they are on the left of the graph. Then, the following plots to be put under cultivation are of decreasing yields. A linear regression enables to find the following fitting production function: $\ln(y) = 5{,}06 - 0{,}35 \times \ln(x)$, with a determination coefficient R^2: 0,74.

This production function can be a classical, easy to manipulate function, for example a Weibull or a Gumbel distribution: those are useful since they have some interesting mathematical properties which make them easy to integrate in a model.

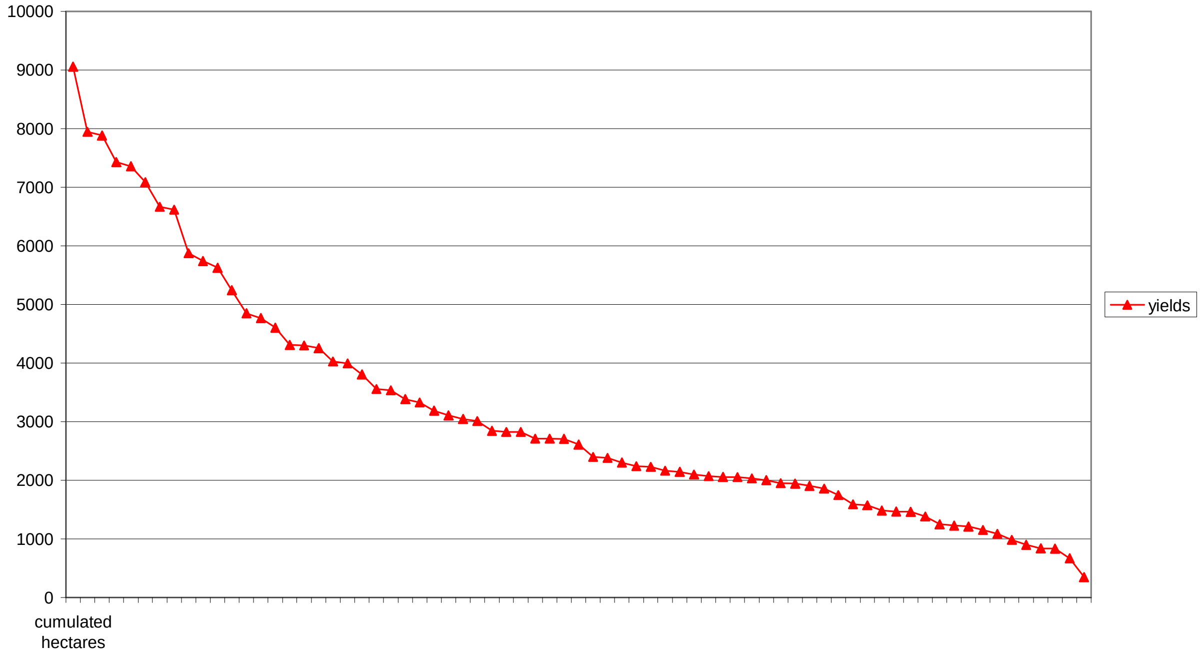


Figure 18. Graph of wheat yield distribution in GTAP countries

6.4.3.3. Use of a plant modeling program

Plant modeling programs can be used with data from spatialized maps to assess the potential of every grid of land within a country. The model ORCHIDEE, developed by the LSCE, should be able to provide such data very soon to produce crop distribution functions for Nexus Land Use.

ORCHIDEE is a global, dynamic model of the continental biosphere, which includes biophysical, biochemical and ecological processes. It was built with 3 preexisting models, and it allows the coexistence of different ecosystems on a same gridpoint. Irrigation is incorporated to the parameterization of the hydrological cycle as a major anthropic factor. It is a key component of the interactions between surface processes, river flow, and atmospheric and oceanic processes. To deal with severely anthropized surfaces, ORCHIDEE is coupled to specific models; including the agronomic model STICS to simulate cereal plots.

The problem with the two solutions that have just been mentioned is that the distribution functions of different crops are not independent. Thus, if we have the decreasing marginal benefit curve for each crop in a country, it is not possible to determine if the plots that are highly fertile for a crop type are the same that are highly fertile for another crop type. The land use decision process can't be accurately rendered.

6.4.3.4. Use of a joint probability function

AgLU found a way to deal with this question (see p.34). It uses a mathematically-friendly yield distribution function to represent the different crop yields existing in each region. It assumes that this function applies (with different parameters) to every land use types (3 types in AgLU: forest, crop and pasture) and every regions (11 in AgLU). Each distribution is characterized by a scale parameter and variance, and covers all potential yields for a crop, whether observed or not. Yield distributions of different land use types may be correlated. Thus, given a joint probability distribution for yields across alternative land uses, the set of potential yields at any particular location can be considered a random sample from that joint probability distribution. Some regions may thus offer a high crop and pasture yield, but low forest yields. Other locations may show the opposite pattern. This method is mathematically challenging, based on some quite strong assumptions, and seems to be hard to use in the case of many land use types, and many regions (because there needs to be as many distribution functions as countries and land use types).

6.4.4. Agro-ecological Zones (AEZ)

An agro-ecological zone is the division of an area of land into smaller units, which have similar characteristics related to land suitability, potential production and environmental impact.

The Food and Agriculture Organization of the United Nations (FAO) with the collaboration of the International Institute for Applied Systems Analysis (IIASA), has developed a global agro-ecological zoning. This zoning work is supposed to be base on recent availability of digital global databases of climatic parameters, topography, soil and terrain, vegetation, and population distribution that define crop suitability and land productivity potentials. But, it hasn’t been possible to find any paper describing how exactly the zoning has been done. It is also impossible to download data, except a JPEG map.

Very fortunately, the GTAP-SAGE model also uses AEZ, and data is available. In this approach, the world is divided into 18 AEZ (6 moisture zones x 3 climate zones). Available data is really precise. For each country, for each AEZ, and for each crop the GTAP-SAGE model produces cultivated surfaces, average crop yields per ha, and average added values per ha.

Advantages of the GTAP AEZ definition are numerous:

- Data is available.
- It keeps the country division, hence the information on national policy distortions.
- It includes a subdivision along geophysical criteria.
- It enables to take climate change impact into account by shifting AEZ position and surface over the world

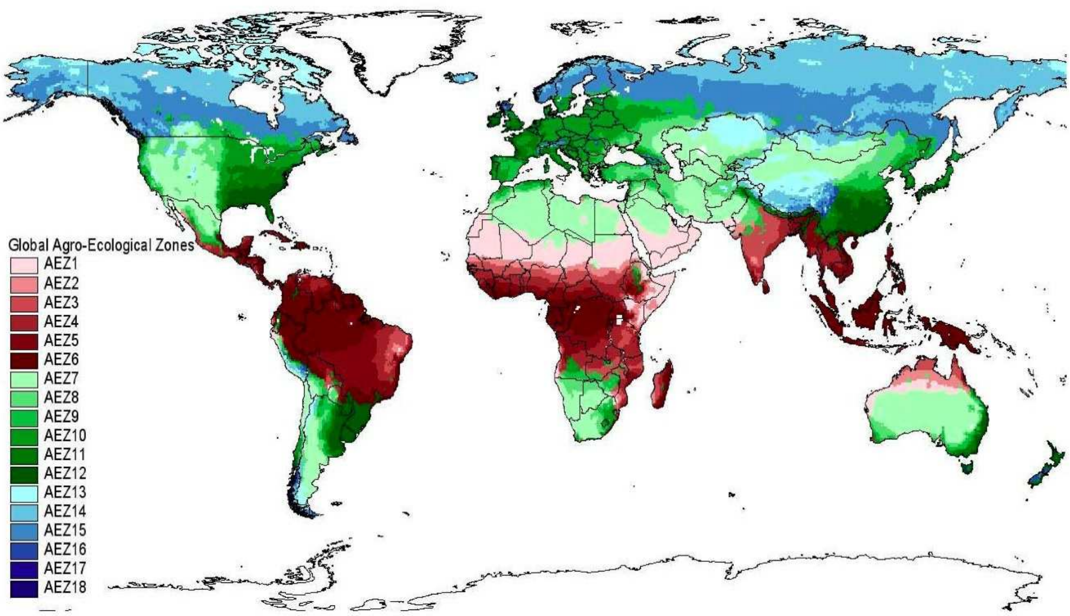
Of course, there are still some problems:

- The AEZ division is only climatic. Land quality is not considered. Furthermore, it doesn’t correspond to any crop potential reality but to a systematic division.
- Data accuracy is doubtful.
- For a country and for an AEZ, benefit and land are constant and we have the same problem as already mentioned previously (see 6.4.2.2, p.71).

Table 2. Definition of global agro-ecological zones used in GTAP

LGP in days	Moisture regime	Climate zone	GTAP class
0-59	Arid	Tropical	AEZ1
		Temperate	AEZ7
		Boreal	AEZ13
60-119	Dry semi-arid	Tropical	AEZ2
		Temperate	AEZ8
		Boreal	AEZ14
120-179	Moist semi-arid	Tropical	AEZ3
		Temperate	AEZ9
		Boreal	AEZ15
180-239	Sub-humid	Tropical	AEZ4
		Temperate	AEZ10
		Boreal	AEZ16
240-299	Humid;	Tropical	AEZ5
		Temperate	AEZ11
		Boreal	AEZ17
>300 days	Humid; year-round growing season	Tropical	AEZ6
		Temperate	AEZ12
		Boreal	AEZ18

Figure 19. The SAGE global map of the 18 AEZs



6.4.5. Spatialization

6.4.5.1. Large-scale, generic crop modeling

Recently, the climate modeling community has started to develop more complex Earth-System models that include marine and terrestrial biogeochemical processes in addition to the representation of atmospheric and oceanic circulation.

The group at the Potsdam Institute for Climate Impact Research (PIK) (Heistermann et al. 2006b) implemented so-called crop functional types (CFTs) to model phenology and growth of the world dominant crop or rangeland types within LPJ (a climate model). The natural vegetation, represented by plant functional types (PFTs), and CFTs can coexist within a mixed grid cell on two different land cover types. PFTs are all mixed within the 'natural' land cover and compete for resources, whereas each CFT is located on a distinct stand with its own water budget within the 'agricultural' land cover. According to the climate, the model estimates several variety-specific parameters in order to ensure that the crop simulated represents the type most likely used by the farmers in that specific environment. Consequently, the model simulates the adaptation by variety selection across the climatic zones and with climate change. The main advantages of this model are that PFTs and CFTs represent a virtual plant that may correspond to different actual crops. The important question of the seeding date is also address by taking into account the seeding date that will maximize yields.

The French group at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) is pursuing a different approach, with their hybrid model consisting of the dynamic global vegetation model ORCHIDEE (see 6.4.3.3, p.74) and the standalone agronomy model STICS. Whenever there is an agricultural land cover type ORCHIDEE is calling STICS and handing over all the necessary climate data STICS needs to calculate crop growth. In return, STICS passes biogeochemical and biophysical variables such as leaf area index, root profile, canopy height, irrigation, and nitrogen stress back to ORCHIDEE. This strategy has been implemented for few different cultivars.

The ORCHIDEE model works but is not totally functional yet. STICS parameterization is done in a non economic fashion by maximizing input use. There are still troubles with tropical crops that STICS doesn't represent really well. Seeding dates used are not calculated but exogenous, so they can adapt to climate change.

6.4.5.2. Advantages and drawbacks of process models

Actually, those models are very useful:

- Inputs are either known: soil type, climate, plant variety, etc. or can be defined: input use, irrigation, technical itinerary.
- Outputs are impossible to know otherwise: crop yield, pollutant and gas emission, impact on soil quality.
- As the models are well localized, the heterogeneity question is well address.

It should also be mentioned that these models give a tremendous quantity of data. For each grid point (around 10 sq. km classically), all around the world, they produce outputs for every crop types under different technical itinerary. This is a lot of data, which necessitates that the model runs a very long time to be produced.

6.4.5.3. How can these models be used in Nexus Land Use?

Firstly, this kind of modeling may help to define in a process-based way the area suitable for different crop varieties.

For instance, knowing what the potential wheat surface is, and how this surface might be evolving with climate change, is a first important step. The PIK team (Heistermann et al. 2006a) addresses this issue by checking if the minimum conditions necessitated by the crop are met. Yet, there are different varieties of a crop type. All those varieties have some common needs (e.g. minimum cumulated radiation). Some varieties have specific needs, such as the presence of few very cold days for winter wheat or the tolerance of a minimum temperature by summer wheat. In the end, a map of potential cultivated land per crop with or without irrigation can be done.

Secondly, instead of using the tremendous data volume, an aggregation can be done. For this goal, the first possibility is to use an AEZ methodology. If we do so, the challenge is to use a better zoning than that of the GTAP-AEZ project. The GTAP-AEZ definition is only based on climatic data, and the accuracy of crop yield data is doubtable. By using the world crop models, it is possible to produce more varied and accurate data, in order to create any AEZ division we find interesting. It is also possible to assess how marginal crop yields evolve with an AEZ.

6.4.5.4. New possibilities?

This part presents another idea that could be interesting to investigate more deeply.

There exist statistic tools which group sets of data vectors by similar class. For instance, the linear discrimining analysis (LDA) theory studies the linear combination of features which the best separate two or more classes of objects or events. According to this approach, the idea is to classify soil types in a way that is not based on geophysical parameters, but on output parameters. This method is used in other research fields, such as genetics, and resembles the ACP technique in statistics.

The ORCHIDEE project could be used in this approach, whereby geophysical parameters and outputs are linked. The link could be ensured by STICS.

To gather similar surfaces together is an interesting approach. Indeed, inside these groups, decreasing average yields can be observed but the reaction (to irrigation, input, land use change, etc.) is the same.

ORCHIDEE is very long to run. However, it makes it possible to have crop yield simulations in each gridpoint all over the world for Nexus’ 8 crop types (and with or without irrigation, and with different technical itineraries, under different global climate condition).

When in possession of all the data, we could simply maximize farmer’s profit at every grid point. The maximization is to be done on a few discontinuous benefit or yield curves at each grid point. Of course, doing that is not very easy. Farmers’ decisions will impact prices, which will impact farmers’ decisions in return. Furthermore, there is a tough initialization work at the first year of the model, to make the model fit the actual data. Yet, those two difficulties have to be addressed anyway. The model will be slow to run, but is this really a problem?

Keeping spatialization (maybe not a very precise one) has advantages. For instance, it allows future addition of new questions such as water availability and biodiversity zones. It has however an important consequence. Maps of future agricultural lands will be obtained and they will be completely false. Land cultivation maps indeed cannot be exact. The reasons for this are multiple.

- Firstly, there is no present accurate crop distribution map that can be used to initialize our model. The SAGE (Ramankutty and Foley 1998) and the PIK teams used satellite-derived land cover data, national and sub-national agricultural inventory data and simulation results to create such maps. Their results are interesting and are the best we have. Yet they don't totally match and they can not be considered as reliable at the most precise level. Of course, the less precise the considered geographical level, the best they match.
- Secondly, our model is only a simulation model, and actual crop yield will depend on criteria we can not take into account (farmers' experience, parasites' activities, etc.).
- Thirdly, even if the model was precisely parameterized, and gave exact potential crop yield, linking yield with benefit is not so easy. The cost of changing cultivars, of distance to storage building, of access to international market, etc., would have to be known. For instance, Brittany is specialized in white meat because harbors are close, but also because the specialization movement created its own dynamics.
- Fourthly, it is pretty obvious that farmers don't maximize yearly costs. Non-economic parameters, such as sentimental attachment to tradition; long-term economic arguments, such as investment, farm size, material existence; personal capacity, such as ability to switch culture, risk aversion; are also important parameters.

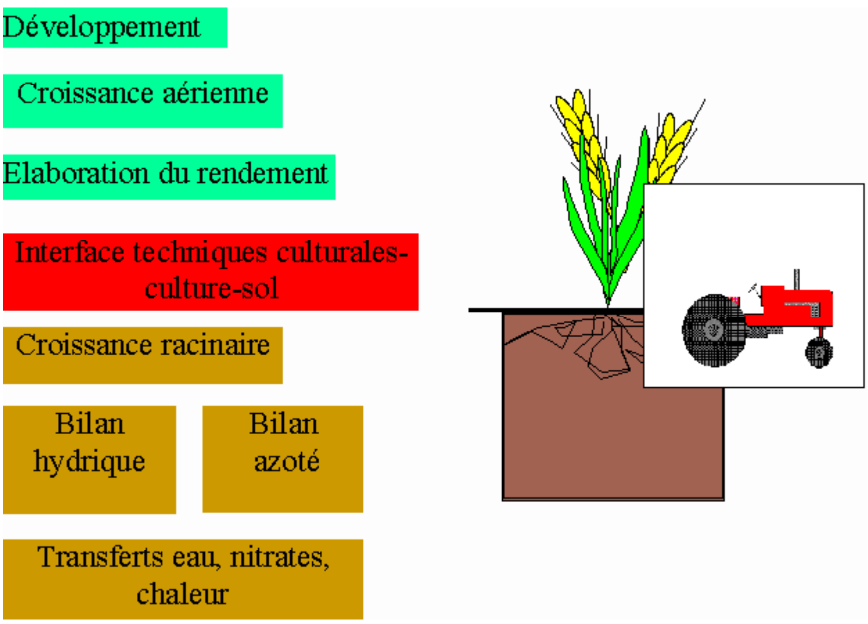


Figure 20. STICS model structure

However, not being able to have accurate maps is not a problem, if we know that the global result (country or continent level) is accurate. As always in prospecting, accuracy is very difficult to check. The global accuracy of our model has to be checked with the evolution over the ten or twenty last years, which is a gigantic work.

What is more, differences between a model's results and reality are often sought for, just because the analysis of these differences may still give a good idea of the processes occurring, and they also highlight the weaknesses of the model and thus show paths for improvements.

6.5. Focus on an important problem: water

6.5.1. Characteristics of water models: different drivers, different scales, addressed issues

The management of water resources is particularly multidimensional, insofar as it includes structural (physical works) as well as non-structural (conservation measures, efficiency improvements, economic instruments etc.) components, and should be conducted in a way that integrates technical, social, environmental and economical dimensions into a coherent framework.

River basin models are used to assess the river basin management with regard to environmental, economic and social effects of alternative water management policies and to explain and understand the underlying processes in the system.

More precisely, the objective of a modeling exercise related to water management is often to maximize the total socio-economic benefit of the river basin. Concerning more specifically agriculture, benefits include the profit from irrigation. The entire system is controlled by institutional decisions on water management policies such as tariffs, allocation decisions, environmental constraints and others. These parameters can be integrated in the model as well.

The hydrologic system provides a more comprehensive and rational setting for the assessment of water resource systems than any other spatial unit defined by political, administrational or local boundaries, and is the appropriate scale for estimating a change in the system performance when water management interventions take place. Knowledge about the hydrological regime of a region or a catchment is a prerequisite for any study of water management. The available water has to be assessed with regard to quantity and quality of groundwater resources, surface water and marine or coastal water.

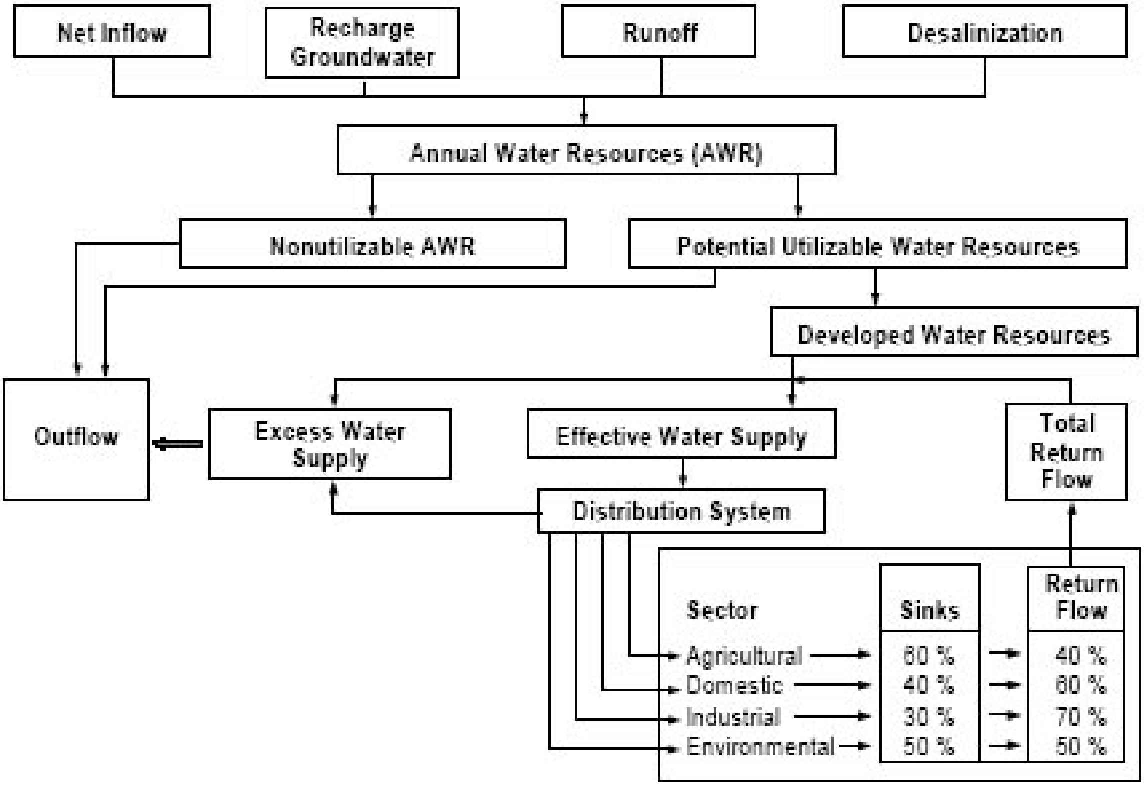
The long-term natural water balance equation for any given catchment can be written as

$$P = ET + Q +/- L + DS$$

Where P is the total precipitation, ET is evapotranspiration, Q is total runoff including groundwater flow, L is leakage from and to the catchment area and DS represents a change in storage in the catchment.

However, the spatial scale of a water balance clearly depends on the objectives of the balance, and the available data and may range from the horizontal balance of a river reach to sub-basins or larger entities.

Figure 21. Schematic overview of water management analysis (Wisser, 2004)



6.5.2. Modeling of water management:

Given the imprecision of the available data, the complexity of the water cycle, and the multiple ways to consider water, many land use models simply do not take water into account, or they account for it in a very simplistic fashion. For example they consider only two possibilities: irrigation provides enough water for the crops, no irrigation constrains yields to a fixed point.

Concerning irrigation, some old studies provide valuable information and methodologies to assess the potential for irrigated cultivation on large spatial scales. All these preexisting approaches apply expert knowledge in order to quantify the limitation which a particular landscape property exerts on the irrigation potential of specific locations. They do not consider the actual distribution of irrigated areas and therefore do not consider how this distribution is actually constrained by the environmental factors. Irrigation is for instance not necessarily applied on locations which are technically optimal or adequate for sustainable soil management. Neither are the water consumption rates for irrigation always compatible with the concept of sustainable river basin management.

While there is at least one continental to global scale hydrological model which explicitly considers the role of irrigation in water consumption (Alcamo, Döll and Siebert), large scale land-use models mostly ignore changes in irrigated areas. According to Heistermann et al. (2006), only few continental to global scale land-use models explicitly include irrigation in their production function, however, dynamic changes are neglected and water resources are rather not related to environmental processes. The IMPACT-Water model is one of the few models which endogenously calculate changes in irrigated areas, however, it operates on the aggregated basis of 36 world regions, which is too coarse for taking into account the geographic variability of water and land constraints to irrigation (Heistermann, 2006).

6.5.2.1. Quantitative assessment of irrigation water needs (Rosegrant et al. 2005)

This part is devoted to the description of how the IMPACT-Water model deals with the issue of water. The IMPACT-Water model stems from the integration, in the IMPACT model of land use, of WSM (water simulation module), that balances water availability and uses within various economic sectors (agriculture, industries, navigation…). Water availability is incorporated as a stochastic variable with observable probability distributions to examine the impact of water availability on food supply, demand and prices.

Water supply and demand and crop production are first assessed at the river-basin scale, with a disaggregation of 69 basins – some regions of particular interest are further divided into sub-basins – and crop production is then summed to the national level, where food demand and trade are modeled (see also p.35, for a description of IMPACT).

(a) Water in the land-use model

Water stands as one of the factors influencing yields and the harvested area. What is more, there is a projected non-price exogenous trend factor gA or gY influencing respectively harvested area and yields, which also depends, among others, on irrigation and water. Water is thus incorporated in the crop area functions in the trend factors and in terms called: crop area reduction due to water stress ΔAC, crop yield reduction due to water stress ΔYC, and a water variable .

For example, the crop area (AC) response is:

$$AC_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PS_{tnj})^{\varepsilon_{ijn}} \times (1 + gA_{tni}) - \Delta AC_{tni}(WAT_{tni})$$

The crop yield YC response has a similar form.

For each year, initially, it is assumed that there is no water shortage, $\Delta AC(W)$ and $\Delta YC(W)$ are zero, and crop area harvested and crop yields are determined based on other parameters. Then water availability for crops is computed thanks to the water component which is described in the two following paragraphs.

(b) The Water Simulation Module: demand side

Concerning specifically the Water Simulation Module (WSM), it is based on a river basin approach. In the original IMPACT-WATER model, the world was divided into 69 major river basins of various sizes.

Irrigation water demand is assessed as crop water requirement, based on hydrologic and agronomic characteristics. Net crop water demand in a basin in a year is calculated based on an empirical crop water requirement function.

Part or all of crop water demand can be satisfied by effective rainfall (PE). Effective rainfall for crop growth can be increased through rainfall harvesting technology. Then net irrigation water demand (NIRWD) is calculated with consideration of effective rainfall use, and salt leaching requirement. Total irrigation water demand (IRWD) is calculated as the ratio NIRWD / BE, in which BE is defined as basin efficiency. BE measures the ratio of beneficial water depletion (crop evapotranspiration and salt leaching) to the total irrigation water depletion at the river basin scale.

The projection of irrigation water demand depends on the changes of irrigated area and cropping patterns, water use efficiency, and rainfall harvest technology.

The model also assesses livestock water demand, based on livestock numbers and water consumptive use per unit of livestock, including beef, milk, pork, poultry, eggs, sheep and goats, and aquaculture fish production. It is assumed that the projection of livestock water demand in each geographical area follows the same growth rate of livestock production. What is more it takes into account the levels of industrial and domestic water uses, and committed flow for environmental, ecological, and navigational uses. A Cobb-Douglas function is used to specify the relationship between water demand and water price, based on price elasticity.

(c) The Water Simulation Module: supply side

As for water supply, WSM focuses on the determination of off-stream water supply for domestic, industrial, livestock and irrigation sectors. This is done in two steps: the first is to determine the total water supply in a basin represented as depletion or consumption in each month of a year; and the second is to allocate the total to different sectors.

The first step is accomplished by taking into account hydrologic processes, such as precipitation, evapotranspiration, and runoff, to assess total renewable water. Anthropogenic impacts – such as water demands, flow regulation through storage, flow diversion, and groundwater pumping, water pollution and other water losses, and water allocation policies – are combined to define the fraction of total renewable water that can be used.

The model is formulated as an optimization model. The objective is to maximize the reliability of water supply. Then, the next step is to determine the water supply available for different sectors. Assuming domestic water is satisfied first, priority is then given to industrial and livestock water demand, whereas irrigation water supply is the residual claimant. Irrigation water is allocated based on profitability of the crop, sensitivity to water stress, and irrigation water demand.

Once the water availability for crops is computed, $\Delta AC(W)$ and $\Delta YC(W)$ are calculated, and crop area (A) and yield (Y) are updated. Thus, crop area and yield are determined endogenously based on water availability, price and other agricultural inputs.

The WSM module of the IMPACT model was found to be very similar to the WATERSIM (de Fraiture 2005) model developed by the IWMI (International Water Management Institute), in that they both try to account for irrigation water needs in a quantitative fashion.

6.5.2.2. A spatio-temporal approach of the assessment of irrigation water needs

Water can be taken into account by modeling the spatio-temporal distribution of irrigated areas, like it was done by the PIK team (Heistermann 2006). This methodology is implemented in the global land-use change model LandSHIFT (Land Simulation to Harmonize and Integrate Freshwater and the Terrestrial Environment), which is a PIK project. The water module stems from the fact that no modeling methodology was found satisfactory enough to account for the evolution of the allocation of irrigated areas as a response to various drivers.

Before focusing on the irrigation model of LandSHIFT, let's have a quick look at the complete model.

(a) LandSHIFT model

The guiding principle of this model is to integrate drivers of land use change at the national level in order to simulate changes in the spatial distribution of land use on a global grid. Drivers of land use change are of economic, technical, technological, social, climatic types. Land use types comprise a set of major crop types, pastures, urban land and forests, shrub lands and deserts. It is assumed that each grid cell is occupied by one dominant land use type. Irrigated and settlement areas are represented by their fraction per grid cell. Each commodity is linked to a particular land use type, i.e. it can be produced only on a cell with this land use type. Each cell thus has a vector of production functions for any commodity. Production is allocated to the most suitable cells by changing the land use type of as many cells as needed to meet the country demand. Competition between sectors (e.g. settlement, crop production, grazing etc.) is modeled by attributing a priority value to each sector that reflects assumptions on its economic importance.

(b) The irrigation model within LandSHIFT

The goal of this model of irrigated areas is to simulate the spatial distribution of irrigated areas as a result of various rivers. More specifically, it intends to allocate a specified expansion of irrigated land within a country to its most suitable location within that country. It is not meant to predict future irrigation patterns, but rather to identify general spatial trends in a consistent and transparent modeling and data framework.

The expansion of irrigated land is specified exogenously. The simulation of irrigated areas is integrated in the crop production module and consists of the following steps: preference ranking; allocation; update of river basin consumption-to-availability ratios. In every time step, the preference ranking first quantifies the preference value of each grid cell for a particular irrigated crop and then ranks the grid cells of each country according to their preference values. The highest ranking grid cells are allocated to the particular crops until the demand for each crop commodity in each country is fulfilled: first, irrigated crops are allocated until either the commodity demand or the exogenously specified irrigation expansion is met. The remaining demand is allocated to rain-fed crops. Finally, the irrigation water consumption is updated for each river basin based on the changes in irrigated areas. The production function of a grid cell for a specific crop at a given time is determined by the potential irrigated and rain-fed crop yield, calculated by the DayCent model (a plant model), the cell area, the fraction of settlement, the fraction of irrigated area, and a technological improvement factor.

A Multi-Criteria-Analysis is used to calculate the preference value of each grid cell for a particular irrigated crop, based on a set of local cell properties (factors). The preference value is defined as the product of two terms: (1) a sum of weighted factors (landscape properties) reflecting the “suitability” for a particular land use type, and (2) land-use constraints (e.g. water or nature policies) connected by multiplication.

The suitability factors that were chosen are the following:

- terrain slope
- river network density: used as a proxy for distance to river and thus for the accessibility of surface water and costs of water transport
- settlement density
- potential irrigated crop yield: computed with the DayCent model, which simulates water-, temperature- and nitrogen- limited yields of major crops on the global scale
- combined soil properties: different attributes of the FAO soil map of the world that assign suitability values between 0 and 1

The land-use constraints that were taken into consideration are the following:

- relative yield gain attained by irrigation: potential increase in crop yield that could be achieved if cropland is irrigated
- water consumption-to-availability ratio: this common indicator of water scarcity reflects the availability of water for irrigation on a basin level, which takes into account the annually renewable freshwater availability per basin before any withdrawal (based on precipitation and evapotranspiration), and the consumption of freshwater by three different sectors
- nature conservation: the protected/unprotected status of the grid cell

(c) Limits and caveats

The main caveat for validating this irrigation model is the lack of appropriate data.

By assuming a maximum allowable irrigated area per country, this model excludes much of the complexity in the decision-making process (particularly from the economics and policy perspective). But even from the strictly spatial perspective, potentially important processes remain either unconsidered or their formulation remains uncertain.

The approach integrates a variety of hydrological, climatic, socio-economic and societal factors. Further analyses should consider basin level time series of irrigation, run-off and consumption as well as significant socio-economic indicators.

The crop yield model used in this modeling framework only considers one cropping cycle per year. Consequently, it cannot reflect the potential yield gains that can be achieved by applying irrigation which would allow for multiple cropping. There is a need to explicitly take into account multiple cropping in the formulation of the production functions of each crop.

There is a need to quantify rain-fed yield insecurity, in order to assess the need for additional irrigation, to account for the intra-annual redistribution of annual water discharge, and how well it coincides with the demand for irrigation water, which varies seasonally, to consider spatial topology within river basins, and especially upstream-downstream linkages in terms of consumption and availability. Maybe the last step would be to take into account inter basin water transfers.

However in most cases, the limiting factor is by any doubt the lack of adequate data.

6.5.2.3. Implications for Nexus Land Use

Taking water into consideration seems to be a very important problem to consider, especially with respect to climate change, and the associated changes in rainfall patterns and irrigation potentials. In the two models reviewed, there seem to be two major problems to tackle: lack of data, and precision of considered geographical scale. To adopt only a quantitative method based on the calculation of crop requirements with more or less complex tools, one is very likely to miss some important problems of local water shortages, local lack of irrigation equipment etc. Crop simulation models are too complex to be able to cope with these problems. That is why the model developed by the PIK is so interesting: it allows for considering water issues at a very precise scale (gridpoint) but in a simple way.

Nexus Land Use will definitely be able obtain data about simulated crop water requirements from STICS, and information about water supply availability from ORCHIDEE. The idea developed by the PIK has to be kept in mind, but for the moment, in the absence of necessary data about irrigation geospatialization, it cannot be implemented.

6.6. Modeling animal production in NEXUS

6.6.1. Importance of livestock in agriculture and the environment

The FAO document "Livestock's long shadow, environmental issues and options", as well as Bouwman's article (2005), review the different aspects of the importance of livestock production. By doing so, they stress the importance of an accurate representation of the livestock sector so as to anticipate future demand of animal products and future impacts of livestock production on the environment.

The global importance of the livestock sector is continuously rising, especially in social and political terms. And indeed, growing populations and incomes, along with changing food preferences, are rapidly increasing demand for livestock products, while globalization is boosting trade in livestock inputs and products. This is due in fact to a high income elasticity of demand for meat and other livestock products – that is, as incomes grow, expenditure on livestock products grows rapidly. Global production of meat is thus projected to more than double from 229 million tons in 1999-2001 to 465 million tons in 2050, and that of milk to grow from 580 to 1043 million tons. However, the livestock sector is not of major importance for the global economy. It accounts for only 40 percent of agricultural gross domestic product.

Nevertheless, the livestock sector emerges as one of the top two or three most significant contributors to the most serious environmental problems, at every scale from local to global.

First of all, the livestock sector is undergoing a process of technical and geographical change. Extensive grazing still occupies and degrades vast areas of land, though there is an increasing trend towards intensification and industrialization. Moreover, livestock production is shifting geographically, closer to consumers and towards the sources of feedstuff. There is also a shift of species, with increasing production of mono-gastric species. These changes contribute to concentrating sources of pollution that create more local damage but are more easily regulated.

What is more, the livestock sector is by far the single largest anthropogenic user of land. In all, livestock production accounts for 70 percent of all agricultural land and 30 percent of the land surface of the planet. Expansion of livestock production is to a large extent responsible for deforestation. In addition, about 20 percent of the world's pastures and rangelands have been degraded, mostly through overgrazing, compaction and erosion created by livestock action.

The livestock sector is also a major player in climate change, as it is responsible for 18 percent of greenhouse gas emissions, measured in CO_2 equivalent. This is a higher share than transport. More precisely, the livestock sector accounts for:

- 9 percent of anthropogenic CO_2 emissions (from land use changes caused by expansion of livestock production),
- 37 percent of anthropogenic methane (from enteric fermentation by ruminants),
- 65 percent of anthropogenic nitrous oxide (from manure).

On the other hand, the livestock sector has a great responsibility in the increase of water use, accounting for over 8 percent of global human water use, mostly for irrigation of feedcrops. It is also a very important source of water pollution, contributing to eutrophication, "dead" zones in coastal areas, degradation of coral reefs, human health problems, emergence of antibiotic resistance and many others. The major sources of pollution are from animal wastes, antibiotics and hormones, chemicals from tanneries, fertilizers and pesticides used for feedcrops, and sediments from eroded pastures.

As the major driver of deforestation, and one of the leading drivers of land degradation, pollution, climate change, over fishing, sedimentation of coastal areas and facilitation of invasions by alien species, the livestock sector has also a great responsibility in the reduction of biodiversity.

Therefore it is very important for our model to comprise a module describing livestock, the way it draws on natural resources, the way quantities of meat and milk produced can be derived, its impacts on the local and global environment.

6.6.2. Theory about animal behavior and alimentation

Domestic ruminants are essentially fed with fodder crops. The energy that a ruminant gets from unlimited fodder depends on 2 major characteristics of the fodder crop:

- Its ingestibility, which is the quantity of fodder ingested. It is expressed in kg of dry matter.
- Its digestibility, that is, the proportion of fodder which disappears in the digestive tube. It determines the energetic value.

In the ration of highly productive animals, fodder crops are completed with more digestible feedstuffs: fruits, grains, roots and divers sub products. These concentrated feedstuffs have a higher concentration of proteins and starch, and a lower content of fibrous components. They are often crushed and turned into granules.

Fodder is all the more digestible as it contains less ligneous tissue, less lignine, and fewer cell walls.

Concentrated feedstuffs are ingested rapidly. Their ingestion requires less rumination since they have been crushed beforehand. They are degraded more rapidly than forages. Thus, the microbian population of the rumen receives fewer cell walls and much more intracellular components with the concentrated feedstuffs than with forages. As a consequence, the microbian population is more abundant, proliferates actively and produces a larger quantity of proteins. Hence, the pH diminishes, especially after the meal, all the more as the concentrated feedstuffs are ingested in higher quantities and in a smaller time space, and as they are richer in starch and other rapidly fermentescible components.

The pH decrease leads to (1) a decrease of the digestibility of the cell walls and (2) digestive and metabolic perturbations.

These perturbations can be avoided by adopting adapted means of preparation and distribution of the feedstuffs, and by making sure that the ration has an acceptable hygienic value. This is an important aspect that has to be taken into account in the modeling of livestock, by adding specific constraints which limit the ingestion of concentrated feedstuff, or establish a relationship between the quantity of concentrated feedstuff ingested and that of fodder crops.

The animal consumes all the concentrated feedstuff it finds, and adapts is forage consumption to that of the concentrated feedstuff. The quantity of forage the animal ingests diminishes in a non linear fashion according to the quantity of concentrated feedstuff ingested, and compared to a ration composed uniquely of forage. The intake of concentrated feedstuff thus first increases the ingestion ability of the animal, and consequently a mixed ration provides more energy than a ration composed uniquely of forage. Production is thus increased at the same time. This phenomenon is valid until a certain threshold, from which the quantity of supplementary dry matter brought into the ration by addition of concentrated feedstuff will stagnated and even decrease, because the consumption of forage diminishes more than the consumption of concentrated feedstuff increases. Hence, the supplementary energy intake will stagnate and then diminish. From that point on, it is no more economically sensible to increase the quantity of concentrated feedstuff. This is due to the decrease of the marginal ingestion of feedstuff (concentrated and forage), and of the digestive efficiency, associated to the marginal consumption of concentrated feedstuff beyond the threshold.

Thus, the animal characteristics which are important in the definition of alimentation needs:

- Species (bovine, sheep, goat)
- Production type (milk, meat),
- Breed, gender, age, weight, weight increase, body condition
- If need be, indicators of lactation (lactation stage, milk potential, quantity and composition of produced milk, i.e. butyrous and protein rate).

The characteristics of the feedstuffs (concentrated or fodder) that constitutes the animal's ration, and that are important to account for, are the following:

- Digestibility value
- Energetic value
- Proteic value

6.6.3. A broadly used representation of livestock: Bouwman's model

Many representations of livestock in land use model are based on Bouwman's model of livestock, as described in his article *Exploring changes in world ruminant production systems* (Bouwman et al. 2005).

6.6.3.1. Model overview

Bouwman is a reference in livestock modeling. This model was developed to describe two aggregated production systems for different world regions, each having typical production characteristics:

(1) the pastoral systems, which depend almost exclusively on grazing,
(2) the mixed and landless systems, that rely on a mix of concentrates (food crops) and roughage (grass, fodder crops, crop residues, and other sources of feedstuffs)

This is an improvement of an earlier version, which is part of the Integrated Model to Assess the Global Environment (IMAGE).

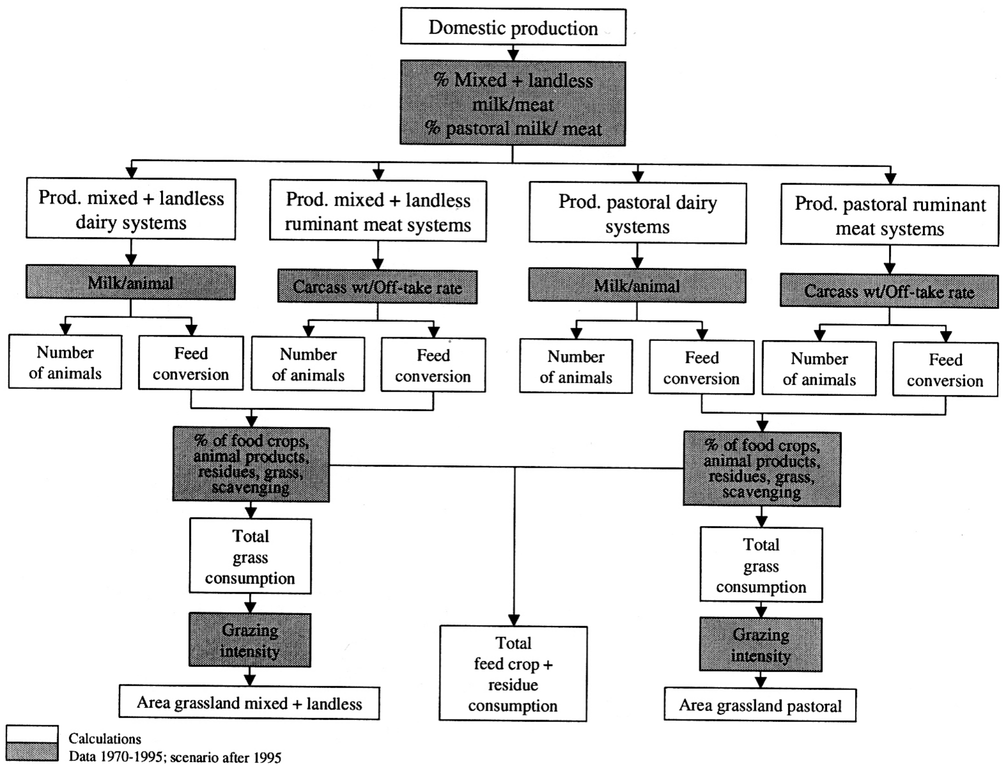
This model is based on the combination of information on animal populations and production characteristics, feed conversion and the composition of animal feed, and geographical information on the distribution of grassland for the period 1970-2030.

Changes in the regional and global grassland area and its use in ruminant production systems for the period until 2030 were assessed by using the IMAGE model with historical data for the period 1970-1995 and data from the study “World Agriculture Towards 2015/2030” of the FAO (Bruinsma, 2003).

The IMAGE model considers sheep and goats as one group of animals, while meat from buffaloes is included in the beef cattle category, and milk from buffaloes is included in dairy cattle. Poultry production includes meat and eggs.

Bouwman describes two aggregated livestock production systems, pastoral systems and mixed + landless systems. Landless ruminant production systems are included in mixed+ landless systems, because they have the same interrelations (food crops, fodder, manure, etc.) with crop and grass production systems as livestock production in mixed systems do. By taking into account different feed efficiencies the total feed requirement, as well as its composition, is calculated for both systems.

Figure 22. Livestock model structure (Bouwman et al., 2005)



In a FAO publication by Seré and Steinfeld (1996) the total animal population and production are provided for different production systems for the early 1990s. The data were aggregated to two broad groups, i.e., pastoral and mixed + landless production systems. The data are provided for seven broad world regions and were disaggregated to the level of 17 world regions of the IMAGE model.

Seré and Steinfeld (1996) also provide data for the growth of animal populations and the production in each production system in the period 1980-1990. These growth rates were used to calculate the population numbers and the production within the different production systems for the years 1970, 1980, and 1990, assuming that the growth rates apply to the full period 1970-1995.

6.6.3.2. Calculation of animal production and feed requirements

The milk production per animal for dairy cattle (MPH, in kg $head^{-1}$ $year^{-1}$) in each production system (s) was calculated from the total milk production (PROD, in kg $year^{-1}$) and population (POP, head) as follows:

$$MPH = PROD_s/POP_{s,dairy}$$

Concerning meat production, the carcass weight (CW, in kg head-1) for each animal category (a) (beef cattle and sheep and goats) within each production system (s) is calculated as follows:

$$CWa,s = PROD_{a,s}/(OR_{a,s} \times POP_{a,s})$$

where OR is the offtake rate (i.e., the fraction of the animal population that is taken out in a given year for slaughter).

Bruinsma's data (2003) for the period 1995-2030 provided a projection of the population growth, of the growth of the per capita gross domestic product, and of the per capita meat consumption. Bruinsma (2003) also provided country data on livestock production, comprising total production of meat for beef cattle and buffaloes, and milk for dairy cattle and buffaloes, and meat production for sheep and goats, pigs and poultry, as well as milk production per animal and off-take rates for meat production. It was assumed that in most of the 17 world regions, the fraction of the animal population and production of meat and milk in pastoral systems will decrease by half of the % change in per capita GDP over the period 1995-2030.

The calculation of total feed required in dairy and beef production is modified from EPA (1994). In this approach, the net energy requirements (in MJ $head^{-1}$ day^{-1}) for dairy cattle are divided into maintenance (NE_m), feeding (NE_f), lactation (NE_t), and pregnancy (NE_p).

The feed requirements for 1995 for sheep and goats were based on estimates used by de Haan et al. (1999) for different production systems and agro-ecosystems. It was assumed that their feed requirement in pastoral and mixed + landless systems for 1970 and 2030 is proportional to that of non-dairy cattle in the corresponding systems.

6.6.3.3. Feed composition

Five feed categories have been distinguished:

- (i) grass, including hay and silage grass
- (ii) food crops and by-products (such as cakes)
- (iii) crop residues and fodder crops
- (iv) animal products
- (v) scavenging

For the period 1970-1995, the FAOSTAT data on feed use of crops, crop by-products and animal products were used. A number of assumptions were made concerning the feed used for the different animal types in the different production systems.

For the period 1995-2030, the same feed composition for each animal category and production system was used, so that changes in total production, feed efficiency of the different animal categories and the gradual trend towards more production in mixed + landless systems will lead to changes in the total demand for the five feed categories.

6.6.3.4. Limits of this approach

The limit we found most striking was the way meat production is taken into account. Half of the bovine meat produced comes from reformed dairy cattle, but Bouwman considers it comes from the non dairy cattle only.

Ruminants appear to need only to fulfill energetic requirements, although all nutrition tables stress that proteic needs are very important.

What is more, the way biological constraints, of ingestion and digestion for example, has been taken into account, is not explained precisely, and thus its reliability can be questioned.

Finally, small ruminants are considered separately from bovines. Isn't it possible to represent all ruminants together with the same set of constraints and production function?

6.6.4. Our approach: towards more precision and more flexibility in describing the ruminants

6.6.4.1. Model overview

We aim at designing a simple and flexible model. Our idea is to group all ruminants (bovines, sheep and goats) in one unique animal category synthesizing all the features of a ruminant. This model starts from the observation that nutrition parameters are the same for any ruminant, dairy and non dairy. Indeed we found that nutrition relationships are more or less the same for all ruminants by making regressions on data obtained from INRA.

Our model follows a few basic principles:

(i) In the short run, the livestock is fixed. This gives a maximum production capacity for milk and meat. It is assumed that it is profitable to produce at the maximum level of this capacity. Prices are fixed.

(ii) Requirements in terms of energy (forage unit milk or meat – UFL[25] or UFV[26] in the French accounting system) and proteins (proteins digestible in the intestine – PDI[27] in the French accounting system), and digestibility constraint, are derived from a given production or demand of milk and meat. Projections of milk and meat production will be given by exogenous scenarios.

(iii) The stock breeder chooses how much he gives to his animals, depending on the prices, and so as to meet the projected production level.

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[25] UFL: Unité Fourrage Lait : one forage unit is the conventional unit which allows for the estimation of the energetic value of a fodder crop with reference to the energetic value of a kilogramme of barley harvested at a mature state equivalent to 1,65 kCal.

[26] UFV: Unité Fourrage Viande

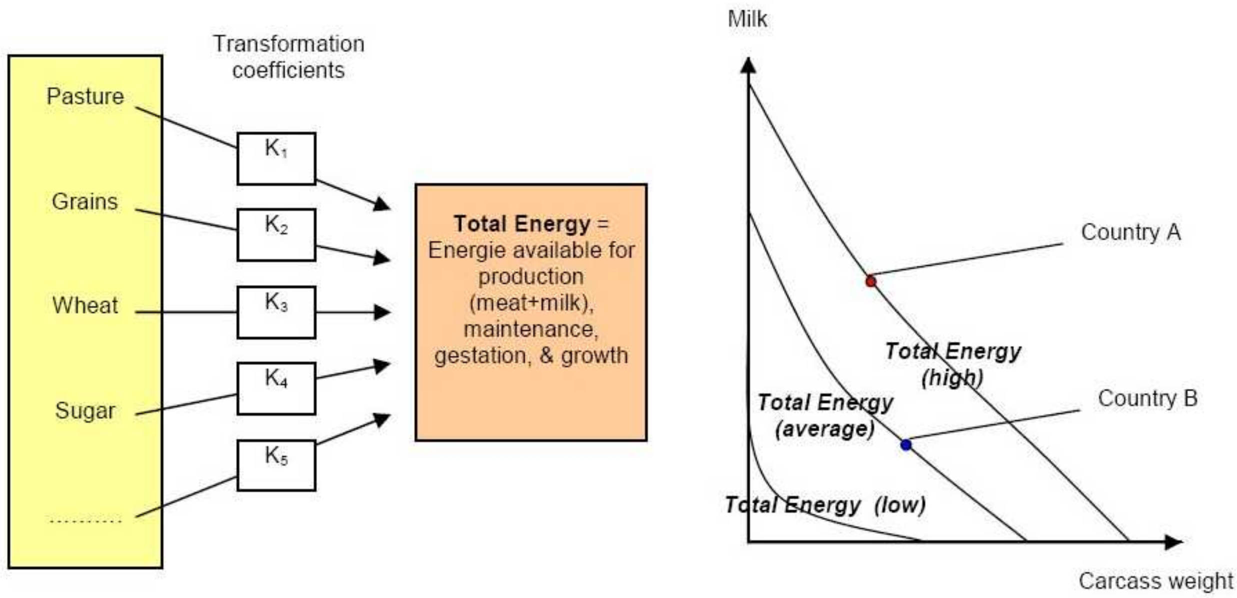
[27] PDI: Protéines Digestibles dans l'Intestin : quantity of proteins that actually gets to the intestine by digestion

(iv) In the long run, the stock breeder can choose the composition of his livestock.

6.6.4.2. Model structure

Just like in Nexus, supply is defined at the national level, and composed of vegetal products (8 categories). Livestock is initially composed of four categories in Nexus Land Use: bovines, sheep and goats, pigs, poultry. In our work we have focused on ruminants, because as they yield two major types of productions (meat and milk), their modeling is the hardest to deal with. Modeling pigs and poultry should be easily derived from the ruminant model or from simple coefficients taken from the INRA database.

Figure 23. Ruminant model structure (representation of the energy part only)



Our typical ruminant is represented by a unique production function describing meat and milk production at the same time. We thus represent an average ruminant, who can produce a whole set of milk and meat production couples, ranging from an "only meat" production point to an "only milk" production point, with all possible intermediaries. The couple "quantity of milk + quantity of meat" produced by the average ruminant of a country depends on the national quantity of energy and proteins fed to the ruminants as a whole. It is also constrained by the total digestibility of the feed products. The energy, proteins and digestibility data are derived from the composition of the total national feed products and transformation coefficients. The shape and level of the production function depends on the composition of the national livestock and the production systems. The production systems also influence the composition of the diet. The position of a country on the production function depends on its level of meat and milk production.

Livestock can be fed either directly on the pasture, or by agricultural productions chosen among the 8 Nexus crop categories, that have been harvested, sometimes transformed, and packaged. Initially, all combinations of feeding products are possible. We will have to add a set of constraints to limit the possibility of ingestion of concentrated feedstuff, or to establish a relationship between the quantity of concentrated feedstuff ingested and that of fodder crops. Each feed product provides a certain level of energy and protein to the animal, which is disposable for maintenance, growth, gestation, lactation, and production.

Most importantly, the typical ruminant is not only one but many animals at the same time, as it represents a mature female, its youngs and the reproductive males gravitating around it.

Assumptions:

- Gestation: 1 gestation per year
- Lactation: the coefficients are the same for all ruminants and equal to that of the cow, which isn't true, but we suppose the error is negligible
- Growth: We assume that the average mature female has one young per year

From Eurostat it is possible to get the following data for European countries: total carcass weight in a year, number of adult females, weight of average adult female, age of death, age of maturity, average weight of young.

(a) Energy requirements

During the lifecycle of one adult female ruminant *i*, the energy consumed is:

$UF_{i,meat,lifetime}$ =

$\left(-55.6+15.5\times W_{female}^{0.75}\right)\times\left(A_{death}-A_{maturity}\right)$ maintenance of the female during its adulthood

+ $\left(107.5+0.2\times W_{death}^{1.5}\right)$ growth of the female until its death

+ $\left(107.5+0.2\times W_{young}^{1.5}\right)\times\left(A_{death}-A_{maturity}\right)$ growth of 1 young/year until their death

+ $\left(1.4+7.6\times W_{female}^{0.5}\right)\times\left(A_{death}-A_{maturity}\right)$ 1 gestation/year

Where:

- W_{female} is the average weight of the adult female ruminant of a country.
- W_{young} is the average weight of other ruminants but female adults.
- W_{death} is the weight of an adult female ruminant at its death.
- A_{death} is the average age of death of an adult female ruminant.
- $A_{maturity}$ is the average age of an adult female ruminant.

Then we derive the UF requirements per year per kg:

$$UF_{meat,year}=\frac{\left[UF_{i,meat,lifetime}\Big/\left(A_{death}-A_{maturity}\right)\right]}{W_{average}}$$ where $W_{average}$ is the average weight of all ruminants.

Then we can derive the total UF requirements per year $UFT_{meat,year}$ which satisfy the meat demand given by a yearly carcass weight TCW_{year} :

$$UFT_{meat,year} = \left(TCW_{year} \big/ UF_{meat,year} \right)$$

To satisfy milk demand, the energy required is simply given by:

$UF_{milk,year} = \left(A_{death} - A_{maturity}\right) \times 0.45 \times Q_{milk}$ where Q_{milk} is the demand for milk

(b) Protein requirements

It follows exactly the same scheme, but with other coefficients:

$PDI_{i,meat,lifetime} =$

$\left(-6664 + 1241 \times W_{female}^{0.75}\right) \times \left(A_{death} - A_{maturity}\right)$ maintenance of the female during its adulthood

$+ \left(18443 + 0.696 \times W_{death}^{2}\right)$ growth of the female until its death

$+ \left(18443 + 0.696 \times W_{young}^{2}\right) \times \left(A_{death} - A_{maturity}\right)$ growth of 1 young/year until their death

$+ \left(-15031 + 12048 \times \log(W_{female})\right) \times \left(A_{death} - A_{maturity}\right)$ 1 gestation/year

$PDI_{milk,year} = \left(A_{death} - A_{maturity}\right) \times 0.53 \times Q_{milk}$

From which is derived the total PDI requirements per year which satisfy the meat demand.

(c) Limitation of ingestion capacity

$UE_{i,meat,lifetime} =$

$\left(-336 + 2.5 \times W_{female} + 0.002 \times W_{female}^{2} + 476 \times \log(W_{female})\right) \times \left(A_{death} - A_{maturity}\right)$

maintenance of the female during its adulthood

$+ \left(-1655 + 9.54 \times W_{death}\right)$ growth of the female until its death

$+ \left(-1655 + 9.54 \times W_{death}\right) \times \left(A_{death} - A_{maturity}\right)$ growth of 1 young/year until their death

$+ \left(72.5 + 0.43 \times W_{female}\right) \times \left(A_{death} - A_{maturity}\right)$ 1 gestation/year

We don't have enough data about the ingestion capacity added by milk production, but we suppose it doesn't add much to the total. We derive from this the total ingestion capacity (IC) corresponding to a total carcass weight.

According to Jarrige (1988) the ratio ingested UE / ingestion capacity (in UE) shouldn't be inferior to 70%. To calculate this ratio, we need to take the UE value of the forage crops (FUE) and to attribute to the concentrated feedstuff a value of 0,5 UE.

Then we have to add to our model the constraint: F x FUE + C x 0,5 ≥ 0,7 x IC, where F is the quantity of forage, and C the quantity of concentrated feedstuff in the ration.

The following figures are some of the linear regression we made with SAS to find the equations cited above.

Figure 24. Linear regression of maintenance needs by weight 0,75

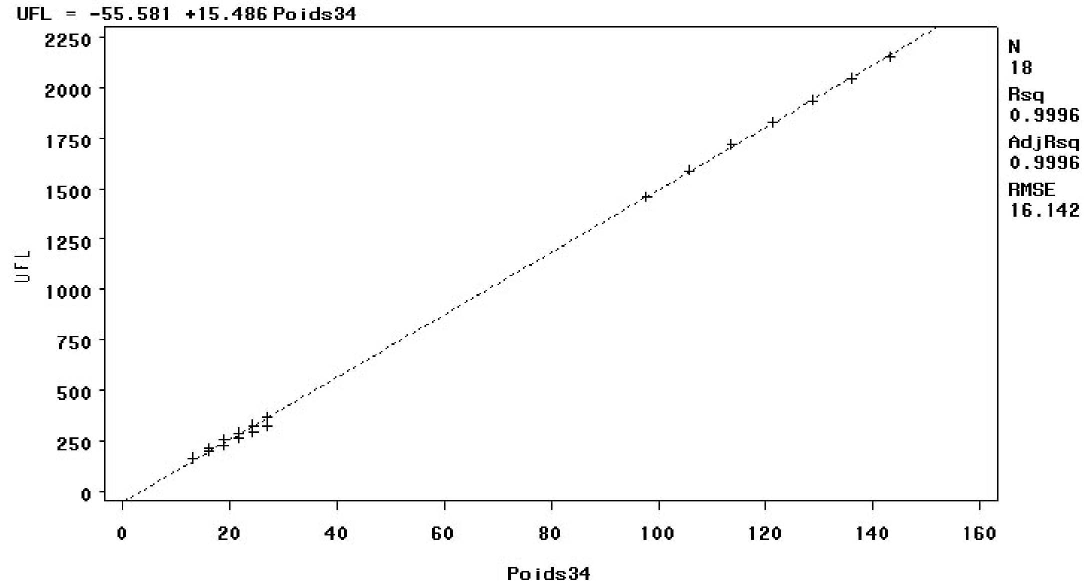


Figure 25. Linear regression of growth needs by weight^{1,5}

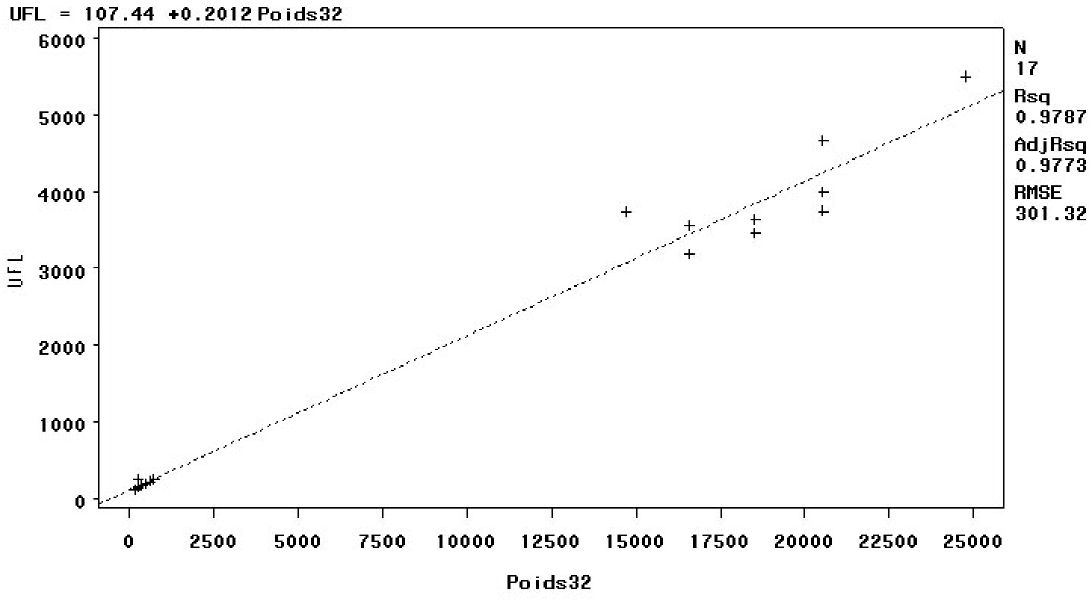
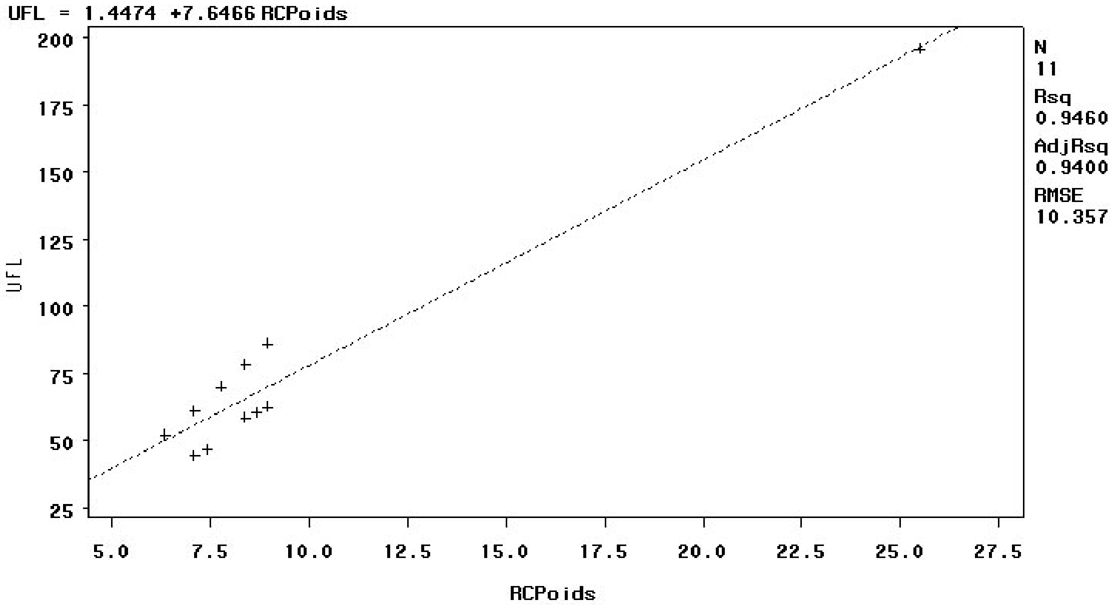


Figure 26. Linear regression of gestation needs by sq root of weight



(d) Crop conversion coefficients

Finally, transformation coefficients for many crops of different varieties were found on Jarrige (1998). We averaged them by big category to produce the following table:

Table 3. Crop transformation coefficients

	average UFV in UFV/kg	average PDI in g/kg	average UE in UE/kg
WHEAT	0,59	53,0	1,010
WHEAT concentrated	1,04	93,2	0,500
GRASS	0,75	73,4	1,076
GRAIN	0,70	57,3	1,142
GRAIN concentrated	1,09	73,4	**0,5**
VEG	0,84	97,4	0,963
VEG concentrated	0,86	94,9	**0,5**
OILSEEDS	0,85	93,5	1,135
OILSEEDS concentrated	1,09	26,0	**0,5**
PRAIRIES	0,81	79,8	1,097
SOYBEAN	0,82	98,0	0,980
SOYBEAN concentrated	1,20	156,0	**0,5**
SUGAR CROPS	1,07	58,3	0,875

Thus, the model will be able to choose between these production types so that the total UFV and PDI values are equal to the total UFV and PDI values derived from the meat and milk demand.

(e) Improvement paths

Although it tries to address some limitations of the Bouwman model, our model has still a wide scope for improvement. For instance, the integration of production systems in the equations should be thoroughly examined. It could be wise to add also some constraints on the rations given to the animals. And indeed in the reality we can observe that there are about 10 major typical rations given to ruminants. We could add these rations as a constraint in the model. But most importantly, the model has to be coded and tested.

7. MATISSE: Methods and Tools for Integrated Sustainability Assessment

MATISSE is a European project which goals are to advance in the science and application of Integrated Sustainability Assessment (ISA) of EU policies. Basically, the idea is to develop new or better tools in order to deliver case-specific sustainability assessments, useful to policy makers and other stakeholders.

The CIRAD[28] is one of MATISSE's member research laboratories. NEXUS Land Use is supposed to be used in MATISSE project to assess the environmental consequences of different agricultural policies.

As a first step, it was asked to use Nexus to evaluate the cost of a 1% decrease of pollutant emissions in the European agriculture.

As NEXUS doesn't run yet, we were asked to develop a very simplified model which would be able to produce the required quantitative results. Before developing this model, the first task was to find present information on the emission of pollutants by the European agriculture, in other words, we spent quite a long time in researching environmental indicators for agriculture.

7.1. Environmental indicators for agriculture

7.1.1. About pollutant emmissions

Nexus is a prospective tool that aims at evaluating the sustainability of agricultural policy choices. Human land uses, especially agriculture, has a strong impact on the environment (see 1.4, p.14). It is therefore essential to find a way to deal with the environmental consequences of the agricultural production techniques.

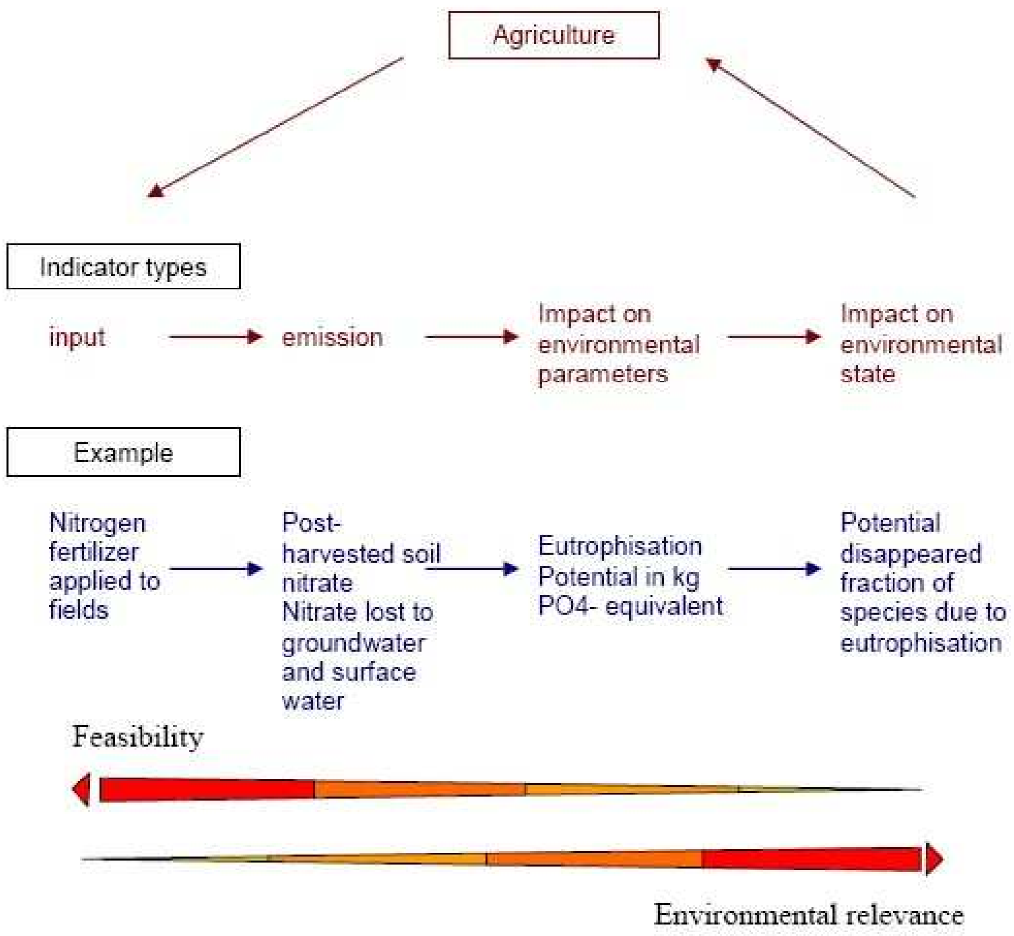
A pollutant is anything that could be harmful to the environment. The environmental damage capacity depends on the quantity, the concentration, the scale, the timing of the pollutant emissions as well as on the environment quality. So classifying an emission in safe or pollutant needs to evaluate the interaction between the emission and the environment at the scientifically right scale.

Unfortunately, agricultural impacts on the environment are somewhat complex and difficult to define. Their complexity is two-fold.

- Scientific uncertainties: the present environmental consequences of farming are not well known scientifically. For instance, nobody is able to define a precise relation between pesticides emissions and bee loss or general biodiversity destruction or human health.

[28] CIRAD : Centre de coopération internationale en recherche agronomique pour le développement

- Lack of financial evaluation: Secondly, and very obviously, environmental impacts are often economics externalities. Not only, they are not taken into account by polluters, but also they are not routinely financially estimated. Moreover agricultural emissions are classically diffuse with a long resilience and become pollutant by accumulation. Then data is difficult to collect. And nobody can link pollutant presences to a damage costs: how much will cost bee loss?



Environmental damage appears to be a broad and confused term. It congregates many different phenomenons which differ by their physical process cycle, their time scale and their geographical scale.

Well awarded of the terrific complexity of considering pollutant emissions (both because of scientific uncertainties and data lack), it was decided to consider input uses.

The question that will be answered becomes: The question: How much would cost a 1% decrease of agricultural inputs in the EU15?

Inputs designate any products famous for being environmental harmful. We will consider here:

- Pesticide use
  - Insecticide use
  - Fungicide use
  - Herbicide use
- Fertilizer use
  - K_2O use
  - P_2O use
  - N use
- Energy use
  - Electricity
  - Gas

7.1.1.1. Geographical scale

Some environmental damages can be very local and create a feedback loop in the exact same area they were made. For example, a bad-managed over-irrigation destroyed soils by salinization in the Dead Sea. As a consequence yields were severely diminished and agriculture was seriously impacted. Since a farm produces on a defined area, it should be possible to integrate easily local impacts in economic calculation… at least when the farmers is well advertised of the feedback between management techniques, environmental damage, and agricultural potential destruction.

But some feedbacks are more regional and therefore they are harder to integrate in economic calculations. Indeed, some locally non-important damages can become critical by accumulation (biodiversity loss has consequences at a regional level by amplifying parasite attacks). What is more, some local changes can create regional changes when they are repeated (important deforestation can modify drastically regional climate).

As the global warming reminds us, others pollutions can be neglected locally (GHG emission) but become a world trouble when they accumulate.

This study is done in the EU15.
The following countries are considered:
Austria, Belgium, Denmark, Finland, France, Germany, United-Kingdom, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden.

Two kind of geographical unit were used:

- country
- country & agro-ecological zone (AEZ)

AEZ is the division of an area of land (here the country) into smaller units, which have similar characteristics related to land suitability, potential production and environmental impact. The AEZ division used here is the one of GTAP Land cover/use. There are 18 AEZs covering six different lengths of growing period spread over three different climatic zones

7.1.1.2. Time scale

Exactly in the same way there are very immediate feedbacks that should be easy to internalize (soil destruction). But other impacts happen in a longer time scale (climate change) and therefore they are much more difficult to evaluate, and to internalize.

7.1.1.3. Physical process cycle

The feedback we are dealing with is pretty simple:

- Agricultural production uses inputs.
- Input uses create emissions.
- Emissions modify environmental parameters.
- Changes in environmental parameters have impacts on agricultural potential in return.

The sequence of events described here form a complex cycle. Into the cycle, only agricultural inputs can be well known since they are submitted to market control, and they are purely dependent on human choices. It should therefore be possible to know which quantity is used and how much it costs.

Emissions are far less well known. As environmental concern increases, research is making progress on estimating them. Yet, they are not submitted to any market law. So they still are very difficult to quantify and impossible to evaluated financially.

Modification of environmental parameters can't be well known. The actual environmental parameters as well as every fluxes and their impacts, reactions, resilience, interactions, etc. are needed for this evaluation. Fluxes for agricultural emissions are already difficult to assess. A few models exist which try to assess those changes. They often are very simplified compared to reality but still they remain very complex, conceptually and mathematically speaking. They concern only a defined area and a type of environmental parameter. For instance, the LSCE works on a model evaluating global changes of physical parameters due to human GHG emissions.

Some environmental changes might be simply impossible to assess. For instance, nobody can really assess the impact of a physical change on biodiversity.

Agricultural potential can be assessed by experimentation or by modeling. Yet, for instance, there is no consensus on how agricultural potentials will respond to an increase of CO_2. So our knowledge stays limited. It has to be improved, in order to be able to understand how land potentiality could respond to different scenarios. Yet, similarly to above, many feedbacks are almost impossible to assess.

For instance, even if we were able to assess the biodiversity loss, the links between biodiversity and agricultural production are not well known or describable. But the links certainly exist, they go through complex and largely unknown competition and mutual aid phenomenon, positive and negative interactions, which change parasites' chances to spread, land quality, water retention, etc.

As usual, the more immediate and local the feedbacks, the best they can be described and known. The other feedbacks, the larger-scale feedbacks Nexus should deal with, are very complex and not enough known.

7.1.1.4. *Farmers' behaviors*

Farmers can take into account in their economic behavior the environmental feedbacks that will impact their revenue. So only the immediate, local or definitive environment impacts are internalized into their calculation.

Since those impacts are already addresses by informed farmers they are not very interesting. In Nexus, it would be much more remarkable to deal with environmental impacts that are not yet internalized. They are the one which create incertitude, they are also the more difficult to treat since, as externalities, they have no market and thus no value. Furthermore, if they haven't been internalized, it is also because their effects are not perfectly known and the scientific incertitude is still important.

As a conclusion, we may say that the less the impact has a direct and quick feedback on the producer, the less the producer takes it into account in his economical calculation. But also, the more they are important in the Nexus model, and unfortunately, the less there is technical data and economical evaluation about them.

7.1.2. Our work on agri-environmental indicators

7.1.2.1. *Data: a very limiting factor*

As it was already said many times on other topics in this report, the true difficulty is data availability.

What is submitted to a market is financially assessable, and then data sets exist and may be available. This is the case for agricultural inputs and could be the case for field potential.

For the two middle steps of the cycle, there is no economic data and often there is no scientific consensus, or, at least, not enough technical description of the physical or biological process.

For example, soil surface nitrogen balance has been proposed as an indicator of nitrogen (N) leaching risk. The N balance is composed of N inputs (slurry/manure, fertilizers, N fixation, N deposition, and N content of the seeds) minus N outputs (harvest, atmospheric losses). However, the calculation of N balance, which could be an indicator of acceptable relevance, is still not completely reliable. It is indeed difficult to obtain N fixation, ammonia volatilization and losses via denitrification. What is more, N leaching is affected by climatic factors (precipitation, frost, temperature) and soil properties (infiltration, capacity, water holding capacity).

Of course, this is softened by the fact that some important physico-ecological models exist.

- Models like STICS use agricultural input data, technical parameterization and defined physico-geochemical conditions to assess emissions.
- By using ORCHIDEE it is possible to obtain the feedback of land use on land potential (at least from a physical point of view since it is mainly through GHG emission and climate change).

Eventually, if a full spatialization is done, ORCHIDEE could be used to assess the impacts of climate change on field potential, and Nexus could be used to evaluate the surface and agricultural techniques, to assess the quantity of emissions in CO_2-equivalent. Regional climate modifications due to important land use changes could also be taken into account. Similarly, if irrigation is taken into account, salinization could be taken into account. Other techniques impacting physico-geochimical environment could be taken into account. Yet, biological and purely ecological interactions are almost impossible to code here since the science is not advanced enough. For instance the importance of biodiversity is difficult to assess, as well as the consequences of eutrophication on global economy etc.

Data sets origins:

• Crop surfaces: ha : per crop type : per country or per country and per AEZ

The GTAP Land cover/use data dataset was used

• Crop yields: kg : per ha : per crop type : per country or per country and per AEZ

The GTAP Land cover/use data dataset was used

Land added value : 2001 US $: per ha : per crop type: per country

The GTAP data version 6 was used.
The land added value evolution (in percentage) until 2025 is furnished by a French laboratory of economy: Equipe de Recherche en Analyse des Systèmes et Modélisation Economiques (ERASME).

• Fertilizer input : N, P_2O_5 and K_2O kg : per ha : per crop type : per country

Data collected by EFMA (the European Fertilizer Manufacturers Association), published by Eurostat. An aggregation was done to have it in GTAP crop sectors.

• Pesticides uses : kg active ingredient: per ha : per crop type : per country

Data collected by ECPA (the European Crop Protection Association), published by Eurostat. An aggregation was done to have it in GTAP crop sectors.

7.1.2.2. A new set of agri-environmental indicators adapted to GTAP

Starting from the observation that the existing sets of environmental indicators are incomplete and imprecise (see also 5.10, p.60), and in the absence of data from STICS and ORCHIDEE, we developed a set of environmental indicators for the European Countries. To build our database, our main sources were: Eurostat, FAOStat, NRdata, IPCC. All this data required a long reaggregation phase, in order to make it compatible with the GTAP crop categories. In the end, some manipulations had to be done to make the quantities x unitary prices correspond to the GTAP cost database. The results are strange, and imputable to our sources of data, many of them resulting from countries' self reporting, or being data reported by producers.

Our indicators comprise:

Pesticide use, Fungicide use, Insecticide use, K_2O use, P_2O use, N use, Electricity, Gas, Oil, Coal, CH_4 emissions, N_2O emissions, CO_2 emissions.

They were used in MATISSE simulation (see further).

7.2. The choice of a world representation

Questions about world representation were described previously. Knowing those different choice possibilities, we have been constrained by data availability.

We don't have data from ORCHIDEE so spatialization was out of the question.

Initializing the model is still a problem, so using decreasing margin added value was not possible. Furthermore, it is not a solution since productions are not independent: they may use the same piece of land.

So we were constrained to use the fixed crop yield and added value per ha method. Using GTAP model data, it is possible to have those data per crop per country and per AEZ. Two models were done: one using data per crop and per county, the other adding the AEZ precision. So there are two geographical units possible: the country and the AEZ in a country.

The model is very simple. GTAP-SAGE provides data about the cultivated surface per geographical unit in 2001. This surface is supposed to be the largest cultivable surface in the geographical unit. Surfaces are also known per crop.

In any geographical unit, we have average crop yield (per crop), average added value (per crop), with or without taxes and subsidies. We know what was the total production in Europe in 2001.

Furthermore, the input level uses per ha, per input types and per crop is known per country (cf 1/). So we know the total input uses in Europe per input types.

The models consist in maximizing the added value under constraints. Constraints are:

- a maximum cultivable surface by geographical unit
- a minimum production at the European level either
    - A: for each crop types,
    - B: for each crop types except the first three (cereal are gather, summed weighted by average kJ/kg),
    - C: for each types except the first four (gather by summing weighted by averogis kJ/kg).

We also put different constraints on input uses: none, same quantity as the present European level per ha, reduction of 1%.

The model was written in GAMS programming code.

7.3. Results

More results are available in the annexes.

As expected, the first results of our model are not correct. When maximizing the added value with no constraints on input uses, we could expect to find the actual added value. But we find a European added value that is 4.976 (per country) or 5.428 (per AEZ & country) times the actual European added values. If our assumptions were true, it would mean the actual situation is far from the economic optimal. It is much more realistic to think it means the model should be rejected.

Table 4. Effect of environmental policies on added values calculated by MATISSE model

	added constraint	Country			Country & AEZ		
		A : Crop	B : Cereal	C : Food	A : Crop	B :Cereal	C :Food
each input < original level	none	1	1	1	1	1	1
	each input < 99% of original level	0,99242834	0,992163009	0,992868059	0,992996498	0,992160706	0,992781521
	insecticides < 99% of original level	0,998918334	0,998432602	0,999490576	0,9989995	0,998530132	0,999037536
	fungicides < 99% of original level	1	1	1	1	1	1
	herbicides < 99% of original level	1	1	1	1	1	1
	all pesticides < 99% of original level	0,998918334	0,998432602	0,999490576	0,9989995	0,998530132	0,999037536
	N < 99% of original level	0,999459167	1	1	0,9989995	0,999020088	0,999518768
	P2O5 < 99% of original level	1	0,998955068	0,999490576	1	0,999020088	0,999037536
	K2O < 99% of original level	0,999459167	0,998955068	0,999490576	1	0,999510044	1
	all fert < 99% of original level	0,999459167	0,997910136	0,998981151	0,9989995	0,998040176	0,998556304
	electricity < 99% of original level	1	1	1	1	1	1
	oil < 99% of original level	0,994050838	0,99477534	0,995415181	0,995497749	0,995100441	0,995668912
	gas < 99% of original level	1	1	1	1	1	1
	coal < 99% of original level	1	1	1	1	1	1
	each energy < 99% of original level	0,994050838	0,99477534	0,995415181	0,995497749	0,995100441	0,995668912
	sum E < 99% sum of original E level	1	1	1	1	1	1

The "per AEZ & country" model is worse than the "per country" model. Thus, the more precise we are, the worse the global result is. The specialization effect, due to uniform added values, can provide explanation to this phenomenon. Very productive areas ensure quantity production and large added value. Yet, it is a bad news when we plan to go on to even more precision with a grid-point spatialization. Maybe, by doing this, we will lose time and accuracy.

When adding the input use constraints (limitation of all European input uses per input types at the level of our data), the maximized European added value is 1,849 (per country) and 1,999 (per AEZ & country) times the present one.

In the table above, level 1 is fixed at the initial condition of the model (constraint of maximum surface by country, and of maximum pollution by country).

The initial condition of the model differs from the observed data, as mentioned previously. The sum of initial added values is known. By assimilating it to the initial conditions, we can derive costs of different environmental policies.

Table 5. Cost of environmental policy calculated by MATISSE model (in $US of 2001)

		Country	Country & AEZ

		Crop	Cereal	Food	Crop	Cereal	Food
each input < original level	each input < 99% of original level	3,35E+08	3,47E+08	3,15E+08	3,10E+08	3,47E+08	3,19E+08
	insecticides < 99% of original level	4,78E+07	6,93E+07	2,25E+07	4,43E+07	6,50E+07	4,26E+07
	all pesticides < 99% of original level	4,78E+07	6,93E+07	2,25E+07	4,43E+07	6,50E+07	4,26E+07
	N < 99% of original level	2,39E+07	0,00E+00	0,00E+00	4,43E+07	4,33E+07	2,13E+07
	K2O < 99% of original level	2,39E+07	4,62E+07	2,25E+07	0,00E+00	2,17E+07	0,00E+00
	all fert < 99% of original level	2,39E+07	9,24E+07	4,51E+07	4,43E+07	8,67E+07	6,39E+07
	oil < 99% of original level	2,63E+08	2,31E+08	2,03E+08	1,99E+08	2,17E+08	1,92E+08
	each energy < 99% of original level	2,63E+08	2,31E+08	2,03E+08	1,99E+08	2,17E+08	1,92E+08

Remarks about the results:

- The method used is not correct, but for the moment it is the best we can do, given our data
- The costs derived are very low, which puts important doubt on the consistency of the data we used

We could improve this very simple model in different ways:

- By getting better data on input uses
- By getting an idea of how the AEZ will evolve in Europe with climate change: this is very difficult to do, it requires to work with the LSCE and their models, but the AEZ disaggregation has been done by the project GTAP-AEZ, and it is not obvious we can do the same type of work
- By doing projections on the evolution of the economic impact of the constraints, as a function of the evolution of the added values. The laboratory of economic research ERASME, of the Ecole Centrale Paris, will give us projections of the relative evolution of added values in Europe.

Conclusion

Past and present human behaviors have been changing the environment in a way which seems irreversible. The consequences of these changes are to be felt more and more intensely in terms of environmental degradation, climate change, depletion of resources etc. These changes might affect agriculture potential particularly severely, because of the effects of environmental changes on soil quality and productivity, water availability and quality, etc. At the same time, the evolution of human population is rapid all over the earth. New very big centers of demand for food are emerging; some types of food demand that used to be somewhat small are going to increase with the increasing wealth of the world population. Some new types of demand for agricultural products have been created, such as biofuels for example.

In this context, agriculture has a very important role to play, as it will have to be able to respond to the future demand for food, energy, and even landscape management. At the same time, it will have to undergo dramatic changes, to be able to adapt to the changing environment. As a consequence, in the future, not only the centers of demand will be totally different, but also the centers of agricultural production are very likely to shift in the long-term, as climate patterns are certainly going to change under the effect of global warming, and the evolution of soil quality might drive some cultures out of some territories.

These phenomenons highlight the need for some reliable tools, allowing for some precise prediction of the new patterns of agricultural production. These tools are meant to give information to policy deciders, to help them anticipate future production patterns and adequately develop technological research, or launch development programs, in order to be able to adapt quickly to the environmental changes.

Technical and economic models of land use perfectly address this rising concern. In this context, it is interesting to try to develop new models of land use, which try to take into account increasingly more factors at an increasingly more precise scale. Nexus Land Use typically is one of these models, in that it aims at taking into account more countries than has ever been done before, with still a big variety of land uses represented, and a good number of different crops. It also considers accounting for complex phenomenon in the most accurate way possible, such as crop water requirements, agricultural pollution, and animal production, in a spatialized way. But this ambition requires a great degree of precision in data and conceptualization. As we have seen for the MATISSE project, which certainly is too simplistic, adding precision doesn’t always add accuracy in the representation of reality. As a consequence, Nexus is still embryonic, and it will require a lot of time and work to be able to make accurate projections some day.

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Annexes : Matisse simulation results

The tables of simulation results are classified:

- per geographic unit: country / country and AEZ
- per production constrain: on each GTAP crop types / on GTAP crop types, cereals being gathered / on GTAP crop types, food products being gathered
- per data type: percentage of European added value loss due to the constrain / in 2001 US $ due to the constrain.

Per country, Cat A, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	1,380	0,212	0,159	0,000	0,372	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,902	0,000	0,000	0,902	0,000
2001	1,380	0,212	0,106	0,000	0,318	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,902	0,000	0,000	0,902	0,000
2002	1,432	0,212	0,159	0,000	0,371	0,000	0,000	0,159	0,000	0,159	0,000	0,000	0,902	0,000	0,000	0,902	0,000
2003	1,379	0,212	0,159	0,000	0,371	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,902	0,000	0,000	0,902	0,000
2004	1,432	0,212	0,159	0,000	0,371	0,000	0,000	0,159	0,000	0,159	0,000	0,000	0,901	0,000	0,000	0,901	0,000
2005	1,431	0,265	0,159	0,000	0,371	0,000	0,053	0,159	0,000	0,159	0,000	0,000	0,901	0,000	0,000	0,901	0,000
2006	1,430	0,212	0,159	0,000	0,371	0,000	0,000	0,159	0,000	0,159	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2007	1,376	0,212	0,159	0,000	0,371	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2008	1,376	0,212	0,106	0,000	0,317	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,899	0,000	0,000	0,899	0,000
2009	1,427	0,211	0,159	0,000	0,370	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,899	0,000	0,000	0,899	0,000
2010	1,373	0,211	0,106	0,000	0,317	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,898	0,000	0,000	0,898	0,000
2011	1,425	0,211	0,158	0,000	0,369	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,950	0,000	0,000	0,950	0,000
2012	1,371	0,211	0,105	0,000	0,369	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,897	0,000	0,000	0,897	0,000
2013	1,371	0,211	0,105	0,000	0,369	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,896	0,000	0,000	0,896	0,000
2014	1,370	0,211	0,105	0,000	0,369	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,896	0,000	0,000	0,896	0,000
2015	1,422	0,211	0,105	0,000	0,369	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,948	0,000	0,000	0,948	0,000
2016	1,369	0,211	0,105	0,000	0,316	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,895	0,000	0,000	0,895	0,000
2017	1,421	0,263	0,158	0,000	0,368	0,000	0,000	0,158	0,000	0,158	0,000	0,000	0,947	0,000	0,000	0,947	0,000
2018	1,421	0,263	0,158	0,000	0,368	0,000	0,000	0,158	0,000	0,158	0,000	0,000	0,947	0,000	0,000	0,947	0,000
2019	1,422	0,211	0,105	0,000	0,316	0,000	0,000	0,105	0,000	0,105	0,000	0,000	0,948	0,000	0,000	0,948	0,000
2020	1,422	0,263	0,105	0,000	0,369	0,000	0,000	0,158	0,000	0,158	0,000	0,000	0,948	0,000	0,000	0,948	0,000
2021	1,423	0,263	0,105	0,000	0,369	0,000	0,000	0,105	0,000	0,158	0,000	0,000	0,948	0,000	0,000	0,948	0,000
2022	1,423	0,264	0,105	0,000	0,369	0,000	0,053	0,158	0,000	0,158	0,000	0,000	1,002	0,000	0,000	1,002	0,000
2023	1,425	0,211	0,106	0,000	0,317	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,950	0,000	0,000	0,950	0,000
2024	1,426	0,264	0,106	0,000	0,370	0,000	0,053	0,158	0,000	0,158	0,000	0,000	0,950	0,000	0,000	0,950	0,000
2025	1,427	0,264	0,106	0,000	0,370	0,000	0,000	0,106	0,000	0,106	0,000	0,000	0,951	0,000	0,000	0,951	0,000

Per country, Cat A, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	6,10E+08	9,39E+07	7,04E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	4,70E+07	0,00E+00	4,70E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2001	6,10E+08	9,39E+07	4,70E+07	0,00E+00	1,41E+08	0,00E+00	0,00E+00	4,70E+07	0,00E+00	4,70E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2002	6,34E+08	9,39E+07	7,04E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	7,04E+07	0,00E+00	7,04E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2003	6,10E+08	9,39E+07	7,04E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	4,69E+07	0,00E+00	4,69E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2004	6,33E+08	9,38E+07	7,04E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	7,04E+07	0,00E+00	7,04E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2005	6,33E+08	1,17E+08	7,03E+07	0,00E+00	1,64E+08	0,00E+00	2,34E+07	7,03E+07	0,00E+00	7,03E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2006	6,33E+08	9,37E+07	7,03E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	7,03E+07	0,00E+00	7,03E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2007	6,09E+08	9,37E+07	7,02E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	4,68E+07	0,00E+00	4,68E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2008	6,08E+08	9,36E+07	4,68E+07	0,00E+00	1,40E+08	0,00E+00	0,00E+00	4,68E+07	0,00E+00	4,68E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2009	6,31E+08	9,35E+07	7,01E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	4,68E+07	0,00E+00	4,68E+07	0,00E+00	0,00E+00	3,97E+08	0,00E+00	0,00E+00	3,97E+08	0,00E+00
2010	6,08E+08	9,35E+07	4,67E+07	0,00E+00	1,40E+08	0,00E+00	0,00E+00	4,67E+07	0,00E+00	4,67E+07	0,00E+00	0,00E+00	3,97E+08	0,00E+00	0,00E+00	3,97E+08	0,00E+00
2011	6,30E+08	9,34E+07	7,00E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,67E+07	0,00E+00	4,67E+07	0,00E+00	0,00E+00	4,20E+08	0,00E+00	0,00E+00	4,20E+08	0,00E+00
2012	6,07E+08	9,33E+07	4,67E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,67E+07	0,00E+00	4,67E+07	0,00E+00	0,00E+00	3,97E+08	0,00E+00	0,00E+00	3,97E+08	0,00E+00
2013	6,06E+08	9,33E+07	4,66E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	4,66E+07	0,00E+00	0,00E+00	3,96E+08	0,00E+00	0,00E+00	3,96E+08	0,00E+00
2014	6,06E+08	9,32E+07	4,66E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	4,66E+07	0,00E+00	0,00E+00	3,96E+08	0,00E+00	0,00E+00	3,96E+08	0,00E+00
2015	6,29E+08	9,32E+07	4,66E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	4,66E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2016	6,06E+08	9,32E+07	4,66E+07	0,00E+00	1,40E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	4,66E+07	0,00E+00	0,00E+00	3,96E+08	0,00E+00	0,00E+00	3,96E+08	0,00E+00
2017	6,29E+08	1,16E+08	6,98E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	6,98E+07	0,00E+00	6,98E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2018	6,29E+08	1,16E+08	6,98E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	6,98E+07	0,00E+00	6,98E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2019	6,29E+08	9,32E+07	4,66E+07	0,00E+00	1,40E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	4,66E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2020	6,29E+08	1,16E+08	4,66E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	6,99E+07	0,00E+00	6,99E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2021	6,29E+08	1,17E+08	4,66E+07	0,00E+00	1,63E+08	0,00E+00	0,00E+00	4,66E+07	0,00E+00	6,99E+07	0,00E+00	0,00E+00	4,19E+08	0,00E+00	0,00E+00	4,19E+08	0,00E+00
2022	6,30E+08	1,17E+08	4,66E+07	0,00E+00	1,63E+08	0,00E+00	2,33E+07	7,00E+07	0,00E+00	7,00E+07	0,00E+00	0,00E+00	4,43E+08	0,00E+00	0,00E+00	4,43E+08	0,00E+00
2023	6,30E+08	9,34E+07	4,67E+07	0,00E+00	1,40E+08	0,00E+00	0,00E+00	4,67E+07	0,00E+00	4,67E+07	0,00E+00	0,00E+00	4,20E+08	0,00E+00	0,00E+00	4,20E+08	0,00E+00
2024	6,31E+08	1,17E+08	4,67E+07	0,00E+00	1,63E+08	0,00E+00	2,34E+07	7,01E+07	0,00E+00	7,01E+07	0,00E+00	0,00E+00	4,20E+08	0,00E+00	0,00E+00	4,20E+08	0,00E+00
2025	6,31E+08	1,17E+08	4,68E+07	0,00E+00	1,64E+08	0,00E+00	0,00E+00	4,68E+07	0,00E+00	4,68E+07	0,00E+00	0,00E+00	4,21E+08	0,00E+00	0,00E+00	4,21E+08	0,00E+00

Per country, Cat B, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	1,313	0,101	0,152	0,000	0,303	0,000	0,000	0,152	0,000	0,152	0,000	0,000	0,859	0,000	0,000	0,859	0,000
2001	1,363	0,151	0,202	0,000	0,303	0,000	0,000	0,202	0,000	0,202	0,000	0,000	0,909	0,000	0,000	0,909	0,000
2002	1,363	0,101	0,202	0,000	0,303	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,858	0,000	0,000	0,858	0,000
2003	1,312	0,101	0,151	0,000	0,303	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,858	0,000	0,000	0,858	0,000
2004	1,362	0,101	0,202	0,000	0,303	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,858	0,000	0,000	0,858	0,000
2005	1,362	0,101	0,202	0,000	0,303	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,857	0,000	0,000	0,857	0,000
2006	1,310	0,101	0,151	0,000	0,302	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,857	0,000	0,000	0,857	0,000
2007	1,360	0,101	0,201	0,000	0,302	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,906	0,000	0,000	0,906	0,000
2008	1,358	0,151	0,201	0,000	0,302	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,905	0,000	0,000	0,905	0,000
2009	1,357	0,151	0,201	0,000	0,302	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,905	0,000	0,000	0,905	0,000
2010	1,355	0,151	0,201	0,000	0,301	0,000	0,000	0,151	0,000	0,151	0,000	0,000	0,904	0,000	0,000	0,904	0,000
2011	1,354	0,150	0,201	0,000	0,301	0,000	0,000	0,201	0,000	0,201	0,000	0,000	0,903	0,000	0,000	0,903	0,000
2012	1,353	0,100	0,150	0,000	0,301	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,902	0,000	0,000	0,902	0,000
2013	1,352	0,150	0,200	0,000	0,300	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,901	0,000	0,000	0,901	0,000
2014	1,351	0,100	0,150	0,000	0,300	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,901	0,000	0,000	0,901	0,000
2015	1,351	0,100	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2016	1,350	0,100	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2017	1,349	0,150	0,150	0,000	0,300	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2018	1,349	0,100	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2019	1,349	0,100	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2020	1,349	0,150	0,150	0,000	0,300	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,950	0,000	0,000	0,950	0,000
2021	1,350	0,100	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2022	1,351	0,100	0,150	0,000	0,250	0,000	0,000	0,100	0,000	0,100	0,000	0,000	0,900	0,000	0,000	0,900	0,000
2023	1,351	0,150	0,150	0,000	0,250	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,951	0,000	0,000	0,951	0,000
2024	1,402	0,150	0,150	0,000	0,300	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,951	0,000	0,000	0,951	0,000
2025	1,404	0,150	0,150	0,000	0,301	0,000	0,000	0,150	0,000	0,150	0,000	0,000	0,952	0,000	0,000	0,952	0,000

Per country, Cat B, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	5,81E+08	4,47E+07	6,70E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,70E+07	0,00E+00	6,70E+07	0,00E+00	0,00E+00	3,80E+08	0,00E+00	0,00E+00	3,80E+08	0,00E+00
2001	6,03E+08	6,70E+07	8,93E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	8,93E+07	0,00E+00	8,93E+07	0,00E+00	0,00E+00	4,02E+08	0,00E+00	0,00E+00	4,02E+08	0,00E+00
2002	6,03E+08	4,47E+07	8,93E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,70E+07	0,00E+00	6,70E+07	0,00E+00	0,00E+00	3,80E+08	0,00E+00	0,00E+00	3,80E+08	0,00E+00
2003	5,81E+08	4,47E+07	6,70E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,70E+07	0,00E+00	6,70E+07	0,00E+00	0,00E+00	3,80E+08	0,00E+00	0,00E+00	3,80E+08	0,00E+00
2004	6,03E+08	4,46E+07	8,93E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,70E+07	0,00E+00	6,70E+07	0,00E+00	0,00E+00	3,79E+08	0,00E+00	0,00E+00	3,79E+08	0,00E+00
2005	6,02E+08	4,46E+07	8,92E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,69E+07	0,00E+00	6,69E+07	0,00E+00	0,00E+00	3,79E+08	0,00E+00	0,00E+00	3,79E+08	0,00E+00
2006	5,80E+08	4,46E+07	6,69E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,69E+07	0,00E+00	6,69E+07	0,00E+00	0,00E+00	3,79E+08	0,00E+00	0,00E+00	3,79E+08	0,00E+00
2007	6,01E+08	4,45E+07	8,91E+07	0,00E+00	1,34E+08	0,00E+00	0,00E+00	6,68E+07	0,00E+00	6,68E+07	0,00E+00	0,00E+00	4,01E+08	0,00E+00	0,00E+00	4,01E+08	0,00E+00
2008	6,01E+08	6,67E+07	8,90E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,67E+07	0,00E+00	6,67E+07	0,00E+00	0,00E+00	4,00E+08	0,00E+00	0,00E+00	4,00E+08	0,00E+00
2009	6,00E+08	6,67E+07	8,89E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,67E+07	0,00E+00	6,67E+07	0,00E+00	0,00E+00	4,00E+08	0,00E+00	0,00E+00	4,00E+08	0,00E+00
2010	6,00E+08	6,66E+07	8,88E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,66E+07	0,00E+00	6,66E+07	0,00E+00	0,00E+00	4,00E+08	0,00E+00	0,00E+00	4,00E+08	0,00E+00
2011	5,99E+08	6,65E+07	8,87E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	8,87E+07	0,00E+00	8,87E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2012	5,99E+08	4,43E+07	6,65E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,65E+07	0,00E+00	6,65E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2013	5,98E+08	6,64E+07	8,86E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,64E+07	0,00E+00	6,64E+07	0,00E+00	0,00E+00	3,99E+08	0,00E+00	0,00E+00	3,99E+08	0,00E+00
2014	5,98E+08	4,43E+07	6,64E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,64E+07	0,00E+00	6,64E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2015	5,97E+08	4,43E+07	6,64E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,64E+07	0,00E+00	6,64E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2016	5,97E+08	4,42E+07	6,63E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2017	5,97E+08	6,63E+07	6,63E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2018	5,97E+08	4,42E+07	6,63E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2019	5,97E+08	4,42E+07	6,63E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2020	5,97E+08	6,63E+07	6,63E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	4,20E+08	0,00E+00	0,00E+00	4,20E+08	0,00E+00
2021	5,97E+08	4,42E+07	6,63E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,63E+07	0,00E+00	6,63E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2022	5,97E+08	4,43E+07	6,64E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	4,43E+07	0,00E+00	4,43E+07	0,00E+00	0,00E+00	3,98E+08	0,00E+00	0,00E+00	3,98E+08	0,00E+00
2023	5,98E+08	6,64E+07	6,64E+07	0,00E+00	1,11E+08	0,00E+00	0,00E+00	6,64E+07	0,00E+00	6,64E+07	0,00E+00	0,00E+00	4,21E+08	0,00E+00	0,00E+00	4,21E+08	0,00E+00
2024	6,20E+08	6,64E+07	6,64E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,64E+07	0,00E+00	6,64E+07	0,00E+00	0,00E+00	4,21E+08	0,00E+00	0,00E+00	4,21E+08	0,00E+00
2025	6,21E+08	6,65E+07	6,65E+07	0,00E+00	1,33E+08	0,00E+00	0,00E+00	6,65E+07	0,00E+00	6,65E+07	0,00E+00	0,00E+00	4,21E+08	0,00E+00	0,00E+00	4,21E+08	0,00E+00

Per country, Cat C, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	0,839	0,099	0,148	0,000	0,296	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,493	0,000	0,000	0,493	0,000
2001	0,888	0,148	0,197	0,000	0,345	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,542	0,000	0,000	0,542	0,000
2002	0,888	0,148	0,197	0,000	0,296	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,493	0,000	0,000	0,493	0,000
2003	0,838	0,099	0,148	0,000	0,296	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,493	0,000	0,000	0,493	0,000
2004	0,887	0,148	0,197	0,000	0,296	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,493	0,000	0,000	0,493	0,000
2005	0,887	0,148	0,197	0,000	0,296	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,493	0,000	0,000	0,493	0,000
2006	0,837	0,098	0,148	0,000	0,295	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,492	0,000	0,000	0,492	0,000
2007	0,885	0,148	0,197	0,000	0,344	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,541	0,000	0,000	0,541	0,000
2008	0,885	0,147	0,197	0,000	0,344	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,541	0,000	0,000	0,541	0,000
2009	0,884	0,098	0,147	0,000	0,295	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,540	0,000	0,000	0,540	0,000
2010	0,883	0,147	0,196	0,000	0,294	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,540	0,000	0,000	0,540	0,000
2011	0,882	0,147	0,196	0,000	0,343	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,539	0,000	0,000	0,539	0,000
2012	0,882	0,147	0,196	0,000	0,294	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,539	0,000	0,000	0,539	0,000
2013	0,881	0,098	0,147	0,000	0,294	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,539	0,000	0,000	0,539	0,000
2014	0,881	0,147	0,147	0,000	0,294	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,538	0,000	0,000	0,538	0,000
2015	0,881	0,147	0,147	0,000	0,294	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,538	0,000	0,000	0,538	0,000
2016	0,881	0,098	0,147	0,000	0,294	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,538	0,000	0,000	0,538	0,000
2017	0,929	0,147	0,196	0,000	0,293	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,587	0,000	0,000	0,587	0,000
2018	0,929	0,147	0,196	0,000	0,293	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,587	0,000	0,000	0,587	0,000
2019	0,881	0,147	0,147	0,000	0,294	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,587	0,000	0,000	0,587	0,000
2020	0,881	0,098	0,147	0,000	0,245	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,538	0,000	0,000	0,538	0,000
2021	0,881	0,098	0,147	0,000	0,245	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,588	0,000	0,000	0,588	0,000
2022	0,931	0,147	0,147	0,000	0,294	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,588	0,000	0,000	0,588	0,000
2023	0,883	0,098	0,147	0,000	0,245	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,589	0,000	0,000	0,589	0,000
2024	0,884	0,098	0,147	0,000	0,245	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,589	0,000	0,000	0,589	0,000
2025	0,934	0,147	0,147	0,000	0,295	0,000	0,000	0,049	0,000	0,049	0,000	0,000	0,639	0,000	0,000	0,639	0,000

Per country, Cat C, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	3,71E+08	4,36E+07	6,55E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2001	3,93E+08	6,54E+07	8,72E+07	0,00E+00	1,53E+08	0,00E+00	0,00E+00	2,18E+07	0,00E+00	2,18E+07	0,00E+00	0,00E+00	2,40E+08	0,00E+00	0,00E+00	2,40E+08	0,00E+00
2002	3,93E+08	6,54E+07	8,72E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	2,18E+07	0,00E+00	2,18E+07	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2003	3,71E+08	4,36E+07	6,54E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2004	3,92E+08	6,54E+07	8,72E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	2,18E+07	0,00E+00	2,18E+07	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2005	3,92E+08	6,54E+07	8,72E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	2,18E+07	0,00E+00	2,18E+07	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2006	3,70E+08	4,36E+07	6,53E+07	0,00E+00	1,31E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2007	3,92E+08	6,53E+07	8,70E+07	0,00E+00	1,52E+08	0,00E+00	0,00E+00	2,18E+07	0,00E+00	2,18E+07	0,00E+00	0,00E+00	2,39E+08	0,00E+00	0,00E+00	2,39E+08	0,00E+00
2008	3,91E+08	6,52E+07	8,69E+07	0,00E+00	1,52E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,39E+08	0,00E+00	0,00E+00	2,39E+08	0,00E+00
2009	3,91E+08	4,35E+07	6,52E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,39E+08	0,00E+00	0,00E+00	2,39E+08	0,00E+00
2010	3,91E+08	6,51E+07	8,68E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,39E+08	0,00E+00	0,00E+00	2,39E+08	0,00E+00
2011	3,90E+08	6,50E+07	8,67E+07	0,00E+00	1,52E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,39E+08	0,00E+00	0,00E+00	2,39E+08	0,00E+00
2012	3,90E+08	6,50E+07	8,67E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2013	3,90E+08	4,33E+07	6,50E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2014	3,90E+08	6,50E+07	6,50E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2015	3,90E+08	6,49E+07	6,49E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,16E+07	0,00E+00	2,16E+07	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2016	3,90E+08	4,33E+07	6,49E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2017	4,11E+08	6,49E+07	8,65E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,16E+07	0,00E+00	2,16E+07	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2018	4,11E+08	6,49E+07	8,65E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,16E+07	0,00E+00	2,16E+07	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2019	3,90E+08	6,49E+07	6,49E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2020	3,90E+08	4,33E+07	6,50E+07	0,00E+00	1,08E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,38E+08	0,00E+00	0,00E+00	2,38E+08	0,00E+00
2021	3,90E+08	4,33E+07	6,50E+07	0,00E+00	1,08E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2022	4,12E+08	6,50E+07	6,50E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2023	3,90E+08	4,34E+07	6,51E+07	0,00E+00	1,08E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,60E+08	0,00E+00	0,00E+00	2,60E+08	0,00E+00
2024	3,91E+08	4,34E+07	6,51E+07	0,00E+00	1,09E+08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,61E+08	0,00E+00	0,00E+00	2,61E+08	0,00E+00
2025	4,13E+08	6,52E+07	6,52E+07	0,00E+00	1,30E+08	0,00E+00	0,00E+00	2,17E+07	0,00E+00	2,17E+07	0,00E+00	0,00E+00	2,83E+08	0,00E+00	0,00E+00	2,83E+08	0,00E+00

Per country & AEZ, Cat A, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	1,122	0,187	0,140	0,000	0,327	0,000	0,094	0,000	0,000	0,094	0,000	0,000	0,608	0,000	0,000	0,608	0,000
2001	1,168	0,234	0,140	0,000	0,374	0,000	0,140	0,047	0,000	0,140	0,000	0,000	0,654	0,000	0,000	0,654	0,000
2002	1,168	0,234	0,140	0,000	0,374	0,000	0,093	0,000	0,000	0,140	0,000	0,000	0,654	0,000	0,000	0,654	0,000
2003	1,168	0,234	0,140	0,000	0,374	0,000	0,140	0,000	0,000	0,140	0,000	0,000	0,654	0,000	0,000	0,654	0,000
2004	1,167	0,233	0,187	0,000	0,373	0,000	0,140	0,047	0,000	0,140	0,000	0,000	0,654	0,000	0,000	0,654	0,000
2005	1,167	0,233	0,140	0,000	0,373	0,000	0,140	0,000	0,000	0,140	0,000	0,000	0,653	0,000	0,000	0,653	0,000
2006	1,119	0,187	0,140	0,000	0,326	0,000	0,093	0,000	0,000	0,093	0,000	0,000	0,606	0,000	0,000	0,606	0,000
2007	1,164	0,233	0,186	0,000	0,373	0,000	0,140	0,047	0,000	0,140	0,000	0,000	0,652	0,000	0,000	0,652	0,000
2008	1,163	0,233	0,140	0,000	0,372	0,000	0,140	0,000	0,000	0,140	0,000	0,000	0,651	0,000	0,000	0,651	0,000
2009	1,116	0,232	0,139	0,000	0,372	0,000	0,093	0,000	0,000	0,093	0,000	0,000	0,651	0,000	0,000	0,651	0,000
2010	1,161	0,232	0,139	0,000	0,371	0,000	0,139	0,000	0,000	0,139	0,000	0,000	0,650	0,000	0,000	0,650	0,000
2011	1,113	0,232	0,139	0,000	0,371	0,000	0,093	0,000	0,000	0,093	0,000	0,000	0,649	0,000	0,000	0,649	0,000
2012	1,158	0,232	0,139	0,000	0,371	0,000	0,139	0,046	0,000	0,139	0,000	0,000	0,648	0,000	0,000	0,648	0,000
2013	1,157	0,231	0,139	0,000	0,370	0,000	0,093	0,000	0,000	0,139	0,000	0,000	0,648	0,000	0,000	0,648	0,000
2014	1,156	0,231	0,139	0,000	0,370	0,000	0,092	0,000	0,000	0,139	0,000	0,000	0,647	0,000	0,000	0,647	0,000
2015	1,155	0,231	0,139	0,000	0,370	0,000	0,092	0,000	0,000	0,139	0,000	0,000	0,647	0,000	0,000	0,647	0,000
2016	1,108	0,231	0,139	0,000	0,369	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,600	0,000	0,000	0,600	0,000
2017	1,153	0,277	0,138	0,000	0,369	0,000	0,138	0,046	0,000	0,138	0,000	0,000	0,646	0,000	0,000	0,646	0,000
2018	1,153	0,277	0,138	0,000	0,415	0,000	0,138	0,046	0,000	0,138	0,000	0,000	0,645	0,000	0,000	0,645	0,000
2019	1,107	0,231	0,138	0,000	0,369	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,645	0,000	0,000	0,645	0,000
2020	1,107	0,231	0,092	0,000	0,369	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,599	0,000	0,000	0,599	0,000
2021	1,107	0,231	0,092	0,000	0,369	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,599	0,000	0,000	0,599	0,000
2022	1,107	0,231	0,092	0,000	0,369	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,645	0,000	0,000	0,645	0,000
2023	1,153	0,277	0,138	0,000	0,369	0,000	0,138	0,046	0,000	0,138	0,000	0,000	0,645	0,000	0,000	0,645	0,000
2024	1,153	0,277	0,138	0,000	0,369	0,000	0,138	0,046	0,000	0,138	0,000	0,000	0,646	0,000	0,000	0,646	0,000
2025	1,108	0,231	0,092	0,000	0,323	0,000	0,092	0,000	0,000	0,092	0,000	0,000	0,646	0,000	0,000	0,646	0,000

Per country & AEZ, Cat A, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	4,54E+08	7,57E+07	5,68E+07	0,00E+00	1,33E+08	0,00E+00	3,79E+07	0,00E+00	0,00E+00	3,79E+07	0,00E+00	0,00E+00	2,46E+08	0,00E+00	0,00E+00	2,46E+08	0,00E+00
2001	4,73E+08	9,46E+07	5,68E+07	0,00E+00	1,51E+08	0,00E+00	5,68E+07	1,89E+07	0,00E+00	5,68E+07	0,00E+00	0,00E+00	2,65E+08	0,00E+00	0,00E+00	2,65E+08	0,00E+00
2002	4,73E+08	9,46E+07	5,68E+07	0,00E+00	1,51E+08	0,00E+00	3,79E+07	0,00E+00	0,00E+00	5,68E+07	0,00E+00	0,00E+00	2,65E+08	0,00E+00	0,00E+00	2,65E+08	0,00E+00
2003	4,73E+08	9,46E+07	5,68E+07	0,00E+00	1,51E+08	0,00E+00	5,68E+07	0,00E+00	0,00E+00	5,68E+07	0,00E+00	0,00E+00	2,65E+08	0,00E+00	0,00E+00	2,65E+08	0,00E+00
2004	4,73E+08	9,45E+07	7,56E+07	0,00E+00	1,51E+08	0,00E+00	5,67E+07	1,89E+07	0,00E+00	5,67E+07	0,00E+00	0,00E+00	2,65E+08	0,00E+00	0,00E+00	2,65E+08	0,00E+00
2005	4,73E+08	9,45E+07	5,67E+07	0,00E+00	1,51E+08	0,00E+00	5,67E+07	0,00E+00	0,00E+00	5,67E+07	0,00E+00	0,00E+00	2,65E+08	0,00E+00	0,00E+00	2,65E+08	0,00E+00
2006	4,53E+08	7,56E+07	5,67E+07	0,00E+00	1,32E+08	0,00E+00	3,78E+07	0,00E+00	0,00E+00	3,78E+07	0,00E+00	0,00E+00	2,46E+08	0,00E+00	0,00E+00	2,46E+08	0,00E+00
2007	4,72E+08	9,43E+07	7,55E+07	0,00E+00	1,51E+08	0,00E+00	5,66E+07	1,89E+07	0,00E+00	5,66E+07	0,00E+00	0,00E+00	2,64E+08	0,00E+00	0,00E+00	2,64E+08	0,00E+00
2008	4,71E+08	9,42E+07	5,65E+07	0,00E+00	1,51E+08	0,00E+00	5,65E+07	0,00E+00	0,00E+00	5,65E+07	0,00E+00	0,00E+00	2,64E+08	0,00E+00	0,00E+00	2,64E+08	0,00E+00
2009	4,52E+08	9,41E+07	5,65E+07	0,00E+00	1,51E+08	0,00E+00	3,77E+07	0,00E+00	0,00E+00	3,77E+07	0,00E+00	0,00E+00	2,64E+08	0,00E+00	0,00E+00	2,64E+08	0,00E+00
2010	4,70E+08	9,40E+07	5,64E+07	0,00E+00	1,50E+08	0,00E+00	5,64E+07	0,00E+00	0,00E+00	5,64E+07	0,00E+00	0,00E+00	2,63E+08	0,00E+00	0,00E+00	2,63E+08	0,00E+00
2011	4,51E+08	9,39E+07	5,64E+07	0,00E+00	1,50E+08	0,00E+00	3,76E+07	0,00E+00	0,00E+00	3,76E+07	0,00E+00	0,00E+00	2,63E+08	0,00E+00	0,00E+00	2,63E+08	0,00E+00
2012	4,69E+08	9,38E+07	5,63E+07	0,00E+00	1,50E+08	0,00E+00	5,63E+07	1,88E+07	0,00E+00	5,63E+07	0,00E+00	0,00E+00	2,63E+08	0,00E+00	0,00E+00	2,63E+08	0,00E+00
2013	4,69E+08	9,37E+07	5,62E+07	0,00E+00	1,50E+08	0,00E+00	3,75E+07	0,00E+00	0,00E+00	5,62E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00
2014	4,68E+08	9,36E+07	5,62E+07	0,00E+00	1,50E+08	0,00E+00	3,75E+07	0,00E+00	0,00E+00	5,62E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00
2015	4,68E+08	9,35E+07	5,61E+07	0,00E+00	1,50E+08	0,00E+00	3,74E+07	0,00E+00	0,00E+00	5,61E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00
2016	4,49E+08	9,35E+07	5,61E+07	0,00E+00	1,50E+08	0,00E+00	3,74E+07	0,00E+00	0,00E+00	3,74E+07	0,00E+00	0,00E+00	2,43E+08	0,00E+00	0,00E+00	2,43E+08	0,00E+00
2017	4,67E+08	1,12E+08	5,60E+07	0,00E+00	1,49E+08	0,00E+00	5,60E+07	1,87E+07	0,00E+00	5,60E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00
2018	4,67E+08	1,12E+08	5,60E+07	0,00E+00	1,68E+08	0,00E+00	5,60E+07	1,87E+07	0,00E+00	5,60E+07	0,00E+00	0,00E+00	2,61E+08	0,00E+00	0,00E+00	2,61E+08	0,00E+00
2019	4,48E+08	9,34E+07	5,60E+07	0,00E+00	1,49E+08	0,00E+00	3,73E+07	0,00E+00	0,00E+00	3,73E+07	0,00E+00	0,00E+00	2,61E+08	0,00E+00	0,00E+00	2,61E+08	0,00E+00
2020	4,48E+08	9,34E+07	3,73E+07	0,00E+00	1,49E+08	0,00E+00	3,73E+07	0,00E+00	0,00E+00	3,73E+07	0,00E+00	0,00E+00	2,43E+08	0,00E+00	0,00E+00	2,43E+08	0,00E+00
2021	4,48E+08	9,34E+07	3,73E+07	0,00E+00	1,49E+08	0,00E+00	3,73E+07	0,00E+00	0,00E+00	3,73E+07	0,00E+00	0,00E+00	2,43E+08	0,00E+00	0,00E+00	2,43E+08	0,00E+00
2022	4,48E+08	9,34E+07	3,73E+07	0,00E+00	1,49E+08	0,00E+00	3,73E+07	0,00E+00	0,00E+00	3,73E+07	0,00E+00	0,00E+00	2,61E+08	0,00E+00	0,00E+00	2,61E+08	0,00E+00
2023	4,67E+08	1,12E+08	5,60E+07	0,00E+00	1,49E+08	0,00E+00	5,60E+07	1,87E+07	0,00E+00	5,60E+07	0,00E+00	0,00E+00	2,61E+08	0,00E+00	0,00E+00	2,61E+08	0,00E+00
2024	4,67E+08	1,12E+08	5,60E+07	0,00E+00	1,49E+08	0,00E+00	5,60E+07	1,87E+07	0,00E+00	5,60E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00
2025	4,49E+08	9,35E+07	3,74E+07	0,00E+00	1,31E+08	0,00E+00	3,74E+07	0,00E+00	0,00E+00	3,74E+07	0,00E+00	0,00E+00	2,62E+08	0,00E+00	0,00E+00	2,62E+08	0,00E+00

Per country & AEZ, Cat B, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	0,985	0,994	0,993	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2001	0,985	0,994	0,993	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2002	0,985	0,994	0,994	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2003	0,985	0,994	0,993	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2004	0,985	0,994	0,993	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2005	0,985	0,994	0,994	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2006	0,985	0,994	0,994	0,996	0,992	0,996	0,996	0,994	0,996	0,994	0,996	0,995	0,990	0,996	0,996	0,990	0,996
2007	0,986	0,994	0,994	0,996	0,992	0,996	0,996	0,995	0,996	0,995	0,996	0,996	0,990	0,996	0,996	0,990	0,996
2008	0,985	0,994	0,994	0,995	0,992	0,995	0,995	0,994	0,995	0,994	0,995	0,995	0,990	0,995	0,995	0,990	0,995
2009	0,986	0,995	0,994	0,996	0,992	0,996	0,996	0,995	0,996	0,995	0,996	0,996	0,991	0,996	0,996	0,991	0,996
2010	0,986	0,995	0,994	0,996	0,993	0,996	0,996	0,995	0,996	0,995	0,996	0,996	0,991	0,996	0,996	0,991	0,996
2011	0,986	0,995	0,994	0,996	0,992	0,996	0,996	0,995	0,996	0,995	0,996	0,996	0,991	0,996	0,996	0,991	0,996
2012	0,926	0,995	0,995	0,996	0,993	0,996	0,996	0,995	0,996	0,995	0,996	0,996	0,991	0,996	0,996	0,991	0,996
2013	0,986	0,995	0,995	0,997	0,993	0,997	0,997	0,995	0,997	0,995	0,997	0,996	0,991	0,997	0,997	0,991	0,997
2014	1,008	1,017	1,017	1,018	1,015	1,018	1,018	1,017	1,018	1,017	1,018	1,018	1,013	1,018	1,018	1,013	1,018
2015	0,926	0,701	0,958	0,997	0,993	0,997	0,997	0,996	0,997	0,996	0,997	0,997	0,992	0,997	0,997	0,992	0,997
2016	0,907	0,996	0,996	0,997	0,994	0,997	0,997	0,996	0,997	0,996	0,997	0,997	0,992	0,997	0,997	0,992	0,997
2017	0,987	0,996	0,996	0,998	0,994	0,998	0,998	0,996	0,998	0,996	0,998	0,997	0,992	0,998	0,998	0,992	0,998
2018	0,987	0,996	0,996	0,998	0,994	0,998	0,998	0,996	0,998	0,996	0,998	0,997	0,993	0,998	0,998	0,992	0,998
2019	0,804	0,996	0,996	0,998	0,994	0,998	0,998	0,996	0,998	0,996	0,998	0,997	0,992	0,998	0,998	0,992	0,998
2020	0,643	0,621	0,800	0,998	0,994	0,998	0,998	0,996	0,998	0,996	0,998	0,998	0,993	0,998	0,998	0,993	0,998
2021	0,988	0,997	0,996	0,999	0,995	0,999	0,999	0,997	0,999	0,997	0,999	0,998	0,993	0,999	0,999	0,993	0,999
2022	0,727	0,758	0,996	0,998	0,995	0,998	0,998	0,997	0,998	0,997	0,998	0,998	0,993	0,998	0,998	0,993	0,998
2023	0,645	0,622	0,996	0,999	0,995	0,999	0,999	0,997	0,999	0,997	0,999	0,998	0,994	0,999	0,999	0,993	0,999
2024	0,632	0,997	0,996	0,999	0,995	0,999	0,999	0,997	0,999	0,997	0,999	0,998	0,994	0,999	0,999	0,993	0,999
2025	0,867	0,997	0,997	0,999	0,996	0,999	0,999	0,998	0,999	0,998	0,999	0,999	0,994	0,999	0,999	0,994	0,999

Per country & AEZ, Cat B, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	1,50E+00	6,36E-01	6,81E-01	4,54E-01	8,17E-01	4,54E-01	4,54E-01	6,36E-01	4,54E-01	6,36E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01
2001	1,50E+00	6,36E-01	6,81E-01	4,54E-01	8,17E-01	4,54E-01	4,54E-01	5,90E-01	4,54E-01	5,90E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01
2002	1,50E+00	5,90E-01	6,36E-01	4,54E-01	8,17E-01	4,54E-01	4,54E-01	5,90E-01	4,54E-01	5,90E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01
2003	1,50E+00	6,35E-01	6,81E-01	4,54E-01	8,17E-01	4,54E-01	4,54E-01	5,90E-01	4,54E-01	5,90E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01	4,54E-01	9,99E-01	4,54E-01
2004	1,50E+00	6,35E-01	6,81E-01	4,54E-01	8,17E-01	4,54E-01	4,54E-01	6,35E-01	4,54E-01	6,35E-01	4,54E-01	4,54E-01	9,98E-01	4,54E-01	4,54E-01	9,98E-01	4,54E-01
2005	1,50E+00	6,35E-01	6,35E-01	4,54E-01	8,16E-01	4,54E-01	4,54E-01	5,90E-01	4,54E-01	5,90E-01	4,54E-01	4,54E-01	9,98E-01	4,54E-01	4,54E-01	9,98E-01	4,54E-01
2006	1,45E+00	5,89E-01	6,35E-01	4,08E-01	7,71E-01	4,08E-01	4,08E-01	5,89E-01	4,08E-01	5,89E-01	4,08E-01	4,53E-01	9,52E-01	4,08E-01	4,08E-01	9,52E-01	4,08E-01
2007	1,45E+00	5,89E-01	6,34E-01	4,08E-01	7,70E-01	4,08E-01	4,08E-01	5,43E-01	4,08E-01	5,43E-01	4,08E-01	4,08E-01	9,51E-01	4,08E-01	4,08E-01	9,51E-01	4,08E-01
2008	1,49E+00	5,88E-01	6,33E-01	4,52E-01	8,14E-01	4,52E-01	4,52E-01	5,88E-01	4,52E-01	5,88E-01	4,52E-01	4,52E-01	9,95E-01	4,52E-01	4,52E-01	9,95E-01	4,52E-01
2009	1,45E+00	5,42E-01	5,87E-01	4,07E-01	7,68E-01	4,07E-01	4,07E-01	5,42E-01	4,07E-01	5,42E-01	4,07E-01	4,07E-01	9,49E-01	4,07E-01	4,07E-01	9,49E-01	4,07E-01
2010	1,40E+00	5,42E-01	5,87E-01	3,61E-01	7,22E-01	3,61E-01	3,61E-01	4,97E-01	3,61E-01	4,97E-01	3,61E-01	3,61E-01	9,03E-01	3,61E-01	3,61E-01	9,03E-01	3,61E-01
2011	1,40E+00	5,41E-01	5,86E-01	3,61E-01	7,66E-01	3,61E-01	3,61E-01	5,41E-01	3,61E-01	5,41E-01	3,61E-01	4,06E-01	9,02E-01	3,61E-01	3,61E-01	9,02E-01	3,61E-01
2012	7,39E+00	4,95E-01	5,41E-01	3,60E-01	7,21E-01	3,60E-01	3,60E-01	4,95E-01	3,60E-01	4,95E-01	3,60E-01	3,60E-01	9,01E-01	3,60E-01	3,60E-01	9,01E-01	3,60E-01
2013	1,35E+00	4,95E-01	5,40E-01	3,15E-01	6,75E-01	3,15E-01	3,15E-01	4,50E-01	3,15E-01	4,50E-01	3,15E-01	3,60E-01	8,55E-01	3,15E-01	3,15E-01	8,55E-01	3,15E-01
2014	-7,81E-01	-1,70E+00	-1,65E+00	-1,84E+00	-1,47E+00	-1,84E+00	-1,84E+00	-1,70E+00	-1,84E+00	-1,70E+00	-1,84E+00	-1,84E+00	-1,29E+00	-1,84E+00	-1,84E+00	-1,29E+00	-1,84E+00
2015	7,37E+00	2,99E+01	4,18E+00	2,70E-01	6,74E-01	2,70E-01	2,70E-01	4,49E-01	2,70E-01	4,49E-01	2,70E-01	3,14E-01	8,09E-01	2,70E-01	2,70E-01	8,09E-01	2,70E-01
2016	9,25E+00	4,04E-01	4,49E-01	2,69E-01	6,29E-01	2,69E-01	2,69E-01	4,04E-01	2,69E-01	4,04E-01	2,69E-01	2,69E-01	7,63E-01	2,69E-01	2,69E-01	8,08E-01	2,69E-01
2017	1,26E+00	3,59E-01	4,49E-01	2,24E-01	5,83E-01	2,24E-01	2,24E-01	3,59E-01	2,24E-01	3,59E-01	2,24E-01	2,69E-01	7,63E-01	2,24E-01	2,24E-01	7,63E-01	2,24E-01
2018	1,26E+00	3,59E-01	4,49E-01	2,24E-01	5,83E-01	2,24E-01	2,24E-01	3,59E-01	2,24E-01	3,59E-01	2,24E-01	2,69E-01	7,18E-01	2,24E-01	2,24E-01	7,63E-01	2,24E-01
2019	1,96E+01	3,59E-01	4,48E-01	2,24E-01	5,83E-01	2,24E-01	2,24E-01	3,59E-01	2,24E-01	3,59E-01	2,24E-01	2,69E-01	7,62E-01	2,24E-01	2,24E-01	7,62E-01	2,24E-01
2020	3,57E+01	3,79E+01	2,00E+01	1,79E-01	5,83E-01	1,79E-01	1,79E-01	3,59E-01	1,79E-01	3,59E-01	1,79E-01	2,24E-01	7,17E-01	1,79E-01	1,79E-01	7,17E-01	1,79E-01
2021	1,17E+00	3,14E-01	3,59E-01	1,35E-01	5,38E-01	1,35E-01	1,35E-01	2,69E-01	1,35E-01	2,69E-01	1,35E-01	1,79E-01	6,73E-01	1,35E-01	1,35E-01	6,73E-01	1,35E-01
2022	2,73E+01	2,42E+01	3,59E-01	1,79E-01	5,38E-01	1,79E-01	1,79E-01	3,14E-01	1,79E-01	3,14E-01	1,79E-01	1,79E-01	6,73E-01	1,79E-01	1,79E-01	6,73E-01	1,79E-01
2023	3,55E+01	3,78E+01	3,59E-01	1,35E-01	4,94E-01	1,35E-01	1,35E-01	2,69E-01	1,35E-01	2,69E-01	1,35E-01	1,80E-01	6,28E-01	1,35E-01	1,35E-01	6,73E-01	1,35E-01
2024	3,68E+01	2,69E-01	3,59E-01	1,35E-01	4,94E-01	1,35E-01	1,35E-01	2,69E-01	1,35E-01	2,69E-01	1,35E-01	1,80E-01	6,29E-01	1,35E-01	1,35E-01	6,74E-01	1,35E-01
2025	1,33E+01	2,70E-01	3,15E-01	8,99E-02	4,49E-01	8,99E-02	8,99E-02	2,25E-01	8,99E-02	2,25E-01	8,99E-02	1,35E-01	5,84E-01	8,99E-02	8,99E-02	6,29E-01	8,99E-02

Per country & AEZ, Cat C, % of European added value loss

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	0,954	1,272	1,090	0,000	0,318	0,000	0,000	0,136	0,000	0,636	0,045	0,000	0,545	0,000	0,000	0,545	0,000
2001	0,954	0,136	0,500	0,000	0,318	0,000	0,000	0,136	0,000	0,136	0,000	0,000	0,545	0,000	0,000	0,545	0,000
2002	4,314	0,136	0,182	0,000	0,318	0,000	0,000	0,091	0,000	0,091	0,000	0,000	0,500	0,000	0,000	0,500	0,772
2003	4,312	0,136	0,182	0,000	0,318	0,000	0,000	0,136	0,045	0,136	0,000	0,000	0,545	0,000	0,000	0,545	0,000
2004	0,953	1,270	0,181	0,000	0,318	0,000	0,000	0,136	0,000	0,136	0,000	0,000	0,544	0,000	0,000	0,544	0,000
2005	0,952	0,136	0,499	0,000	0,317	0,000	0,000	0,136	0,000	0,136	0,000	0,000	0,544	0,000	0,000	0,544	0,000
2006	0,952	0,136	0,408	0,000	0,317	0,000	0,000	0,091	0,000	0,635	0,000	0,000	0,499	0,000	0,000	0,499	0,000
2007	0,951	1,268	1,087	0,000	0,317	0,000	0,000	0,091	0,000	0,091	0,000	2,264	0,498	0,000	0,000	0,498	0,000
2008	0,950	0,136	0,181	0,000	0,317	0,000	0,000	0,136	0,000	0,136	0,000	0,000	0,543	0,000	0,000	0,543	0,000
2009	4,293	0,136	0,723	0,000	0,316	0,000	0,000	0,090	0,000	0,090	0,136	0,000	0,542	0,000	0,000	0,542	0,000
2010	0,948	0,135	0,135	0,000	0,271	0,000	0,000	0,090	0,000	0,632	0,000	0,000	0,497	0,000	0,000	0,497	0,000
2011	0,947	0,135	0,180	0,000	0,316	0,000	0,000	0,135	0,000	0,135	0,000	0,000	0,541	0,000	0,000	0,541	0,000
2012	0,946	0,135	0,180	0,000	0,315	0,000	0,000	0,090	0,000	0,090	0,045	2,297	0,541	0,000	0,000	3,694	0,000
2013	0,945	1,260	2,160	0,000	0,315	0,000	0,000	0,090	0,000	0,090	0,000	0,000	0,495	0,000	0,000	0,495	0,000
2014	-1,194	-2,021	-1,975	-2,159	-1,654	-2,159	-2,159	-1,516	-2,159	-2,067	-2,067	-2,159	-1,608	-1,286	-1,286	-1,608	-2,159
2015	0,943	0,135	0,449	0,000	0,314	0,000	0,000	0,629	0,090	0,180	0,449	0,000	0,539	0,000	0,000	0,539	0,000
2016	0,943	0,135	0,135	0,000	0,314	0,000	0,000	0,090	0,000	0,135	0,718	0,000	0,494	0,000	0,000	0,494	0,853
2017	0,943	0,135	0,269	0,000	0,494	0,000	0,000	0,090	0,000	0,135	0,718	0,000	0,494	0,000	0,000	0,494	0,853
2018	0,942	0,135	0,135	0,000	0,314	0,000	0,000	0,090	0,000	0,090	0,090	0,000	0,493	0,000	0,000	0,493	0,000
2019	0,987	1,121	1,525	0,000	0,314	0,000	0,000	0,628	0,987	0,987	0,000	0,000	0,538	0,000	0,000	0,538	0,000
2020	0,987	0,179	0,179	0,000	0,314	0,000	0,000	0,628	0,090	0,224	0,000	0,000	0,942	1,166	1,166	0,538	0,762
2021	0,942	0,135	0,135	0,000	0,269	0,000	0,000	0,449	0,000	0,135	0,000	0,000	0,493	0,000	0,000	0,493	0,359
2022	0,987	0,179	0,179	0,000	0,314	0,000	0,000	0,135	0,000	0,135	0,000	0,000	0,538	0,359	0,359	0,538	0,359
2023	0,987	0,135	0,359	0,000	0,314	0,000	0,000	0,449	0,000	0,449	0,000	0,000	0,539	0,000	0,000	0,853	0,000
2024	0,988	0,180	0,180	0,000	0,314	0,000	0,000	0,180	0,000	0,180	0,000	0,045	0,539	0,404	0,404	0,539	0,404
2025	0,989	0,135	0,135	0,000	0,270	0,000	0,000	0,135	0,000	0,135	0,000	0,000	0,539	0,000	0,000	0,539	0,000

Per country & AEZ, Cat C, cost of emission reduction at the European level in 2001 US $

year	each input < 99% of original level	insecticides < 99% of original level	fungicides < 99% of original level	herbicides < 99% of original level	each pesticides < 99% of original level	sum pesticides < 99% sum original level	N < 99% of original level	P2O5 < 99% of original level	K2O < 99% of original level	each fert < 99% of original level	sum fert < 99% sum original level	electricity < 99% of original level	oil < 99% of original level	gas < 99% of original level	coal < 99% of original level	each energy < 99% of original level	sum E < 99% sum original E level
2000	3,86E+08	5,15E+08	4,41E+08	0,00E+00	1,29E+08	0,00E+00	0,00E+00	5,52E+07	0,00E+00	2,58E+08	1,84E+07	0,00E+00	2,21E+08	0,00E+00	0,00E+00	2,21E+08	0,00E+00
2001	3,86E+08	5,52E+07	2,02E+08	0,00E+00	1,29E+08	0,00E+00	0,00E+00	5,52E+07	0,00E+00	5,52E+07	0,00E+00	0,00E+00	2,21E+08	0,00E+00	0,00E+00	2,21E+08	0,00E+00
2002	1,75E+09	5,52E+07	7,36E+07	0,00E+00	1,29E+08	0,00E+00	0,00E+00	3,68E+07	0,00E+00	3,68E+07	0,00E+00	0,00E+00	2,02E+08	0,00E+00	0,00E+00	2,02E+08	3,13E+08
2003	1,75E+09	5,52E+07	7,35E+07	0,00E+00	1,29E+08	0,00E+00	0,00E+00	5,52E+07	1,84E+07	5,52E+07	0,00E+00	0,00E+00	2,21E+08	0,00E+00	0,00E+00	2,21E+08	0,00E+00
2004	3,86E+08	5,15E+08	7,35E+07	0,00E+00	1,29E+08	0,00E+00	0,00E+00	5,51E+07	0,00E+00	5,51E+07	0,00E+00	0,00E+00	2,21E+08	0,00E+00	0,00E+00	2,21E+08	0,00E+00
2005	3,86E+08	5,51E+07	2,02E+08	0,00E+00	1,29E+08	0,00E+00	0,00E+00	5,51E+07	0,00E+00	5,51E+07	0,00E+00	0,00E+00	2,20E+08	0,00E+00	0,00E+00	2,20E+08	0,00E+00
2006	3,86E+08	5,51E+07	1,65E+08	0,00E+00	1,29E+08	0,00E+00	0,00E+00	3,67E+07	0,00E+00	2,57E+08	0,00E+00	0,00E+00	2,02E+08	0,00E+00	0,00E+00	2,02E+08	0,00E+00
2007	3,85E+08	5,14E+08	4,40E+08	0,00E+00	1,28E+08	0,00E+00	0,00E+00	3,67E+07	0,00E+00	3,67E+07	0,00E+00	9,17E+08	2,02E+08	0,00E+00	0,00E+00	2,02E+08	0,00E+00
2008	3,85E+08	5,50E+07	7,33E+07	0,00E+00	1,28E+08	0,00E+00	0,00E+00	5,50E+07	0,00E+00	5,50E+07	0,00E+00	0,00E+00	2,20E+08	0,00E+00	0,00E+00	2,20E+08	0,00E+00
2009	1,74E+09	5,49E+07	2,93E+08	0,00E+00	1,28E+08	0,00E+00	0,00E+00	3,66E+07	0,00E+00	3,66E+07	5,49E+07	0,00E+00	2,20E+08	0,00E+00	0,00E+00	2,20E+08	0,00E+00
2010	3,84E+08	5,49E+07	5,49E+07	0,00E+00	1,10E+08	0,00E+00	0,00E+00	3,66E+07	0,00E+00	2,56E+08	0,00E+00	0,00E+00	2,01E+08	0,00E+00	0,00E+00	2,01E+08	0,00E+00
2011	3,83E+08	5,48E+07	7,30E+07	0,00E+00	1,28E+08	0,00E+00	0,00E+00	5,48E+07	0,00E+00	5,48E+07	0,00E+00	0,00E+00	2,19E+08	0,00E+00	0,00E+00	2,19E+08	0,00E+00
2012	3,83E+08	5,47E+07	7,30E+07	0,00E+00	1,28E+08	0,00E+00	0,00E+00	3,65E+07	0,00E+00	3,65E+07	1,82E+07	9,30E+08	2,19E+08	0,00E+00	0,00E+00	1,50E+09	0,00E+00
2013	3,83E+08	5,10E+08	8,75E+08	0,00E+00	1,28E+08	0,00E+00	0,00E+00	3,65E+07	0,00E+00	3,65E+07	0,00E+00	0,00E+00	2,01E+08	0,00E+00	0,00E+00	2,01E+08	0,00E+00
2014	-4,84E+08	-8,19E+08	-8,00E+08	-8,74E+08	-6,70E+08	-8,74E+08	-8,74E+08	-6,14E+08	-8,74E+08	-8,37E+08	-8,37E+08	-8,74E+08	-6,51E+08	-5,21E+08	-5,21E+08	-6,51E+08	-8,74E+08
2015	3,82E+08	5,46E+07	1,82E+08	0,00E+00	1,27E+08	0,00E+00	0,00E+00	2,55E+08	3,64E+07	7,28E+07	1,82E+08	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2016	3,82E+08	5,46E+07	5,46E+07	0,00E+00	1,27E+08	0,00E+00	0,00E+00	3,64E+07	0,00E+00	5,46E+07	2,91E+08	0,00E+00	2,00E+08	0,00E+00	0,00E+00	2,00E+08	3,46E+08
2017	3,82E+08	5,45E+07	1,09E+08	0,00E+00	2,00E+08	0,00E+00	0,00E+00	3,64E+07	0,00E+00	5,45E+07	2,91E+08	0,00E+00	2,00E+08	0,00E+00	0,00E+00	2,00E+08	3,45E+08
2018	3,82E+08	5,45E+07	5,45E+07	0,00E+00	1,27E+08	0,00E+00	0,00E+00	3,63E+07	0,00E+00	3,63E+07	3,63E+07	0,00E+00	2,00E+08	0,00E+00	0,00E+00	2,00E+08	0,00E+00
2019	4,00E+08	4,54E+08	6,18E+08	0,00E+00	1,27E+08	0,00E+00	0,00E+00	2,54E+08	4,00E+08	4,00E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00
2020	4,00E+08	7,27E+07	7,27E+07	0,00E+00	1,27E+08	0,00E+00	0,00E+00	2,54E+08	3,63E+07	9,08E+07	0,00E+00	0,00E+00	3,81E+08	4,72E+08	4,72E+08	2,18E+08	3,09E+08
2021	3,82E+08	5,45E+07	5,45E+07	0,00E+00	1,09E+08	0,00E+00	0,00E+00	1,82E+08	0,00E+00	5,45E+07	0,00E+00	0,00E+00	2,00E+08	0,00E+00	0,00E+00	2,00E+08	1,45E+08
2022	4,00E+08	7,27E+07	7,27E+07	0,00E+00	1,27E+08	0,00E+00	0,00E+00	5,45E+07	0,00E+00	5,45E+07	0,00E+00	0,00E+00	2,18E+08	1,45E+08	1,45E+08	2,18E+08	1,45E+08
2023	4,00E+08	5,45E+07	1,45E+08	0,00E+00	1,27E+08	0,00E+00	0,00E+00	1,82E+08	0,00E+00	1,82E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	3,45E+08	0,00E+00
2024	4,00E+08	7,27E+07	7,27E+07	0,00E+00	1,27E+08	0,00E+00	0,00E+00	7,27E+07	0,00E+00	7,27E+07	0,00E+00	1,82E+07	2,18E+08	1,64E+08	1,64E+08	2,18E+08	1,64E+08
2025	4,00E+08	5,46E+07	5,46E+07	0,00E+00	1,09E+08	0,00E+00	0,00E+00	5,46E+07	0,00E+00	5,46E+07	0,00E+00	0,00E+00	2,18E+08	0,00E+00	0,00E+00	2,18E+08	0,00E+00