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The impact of global drivers on agriculture and land-use

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Résumé

Dans un contexte de tensions à venir sur la ressource foncière, l'objectif de cette thèse est d'étudier l'influence des déterminants globaux, que sont la mondialisation et le changement climatique, sur l'agriculture et les changements d'usages des sols. Pour mener cette étude, un nouveau modèle d'usage des sols, appelé "Nexus Land-Use", est développé afin de permettre une vision cohérente du système socio-biosphérique.

Les modèles existants sont d'abord examinés, avec pour objectif d'évaluer leur capacité à estimer les changements indirects d'affectation des terres liés aux biocarburants (CIAT). Les CIAT constituent un symptôme caractéristique de l'influence des déterminants globaux en ce qu'ils résultent des flux internationaux d'échanges. Leur estimation représente un défi pour les modélisateurs car elle nécessite une vision intégrée du système agricole, avec une prise en compte au niveau global des côtés offre et demande du secteur agricole. Il apparaît que malgré des progrès significatifs sur la représentation de l'offre de terres et du secteur de la bioénergie, les modèles existants ne parviennent pas encore à fournir une évaluation robuste des CIAT, du fait notamment d'estimations divergentes des élasticité-prix des rendements agricoles et de la demande alimentaire.

Pour répondre au défi posé par la modélisation des déterminants globaux, cette thèse présente le modèle Nexus Land-Use. Fondé sur une représentation des mécanismes d'intensification agricole, à la fois au niveau de la production végétale et animale, ce modèle a pour caractéristiques de combiner au sein d'un seul outil l'économie et la biophysique, et de représenter les effets multi-échelles en intégrant l'hétérogénéité locale dans une architecture globale. La spécificité de ce modèle est également de calculer la rente foncière de manière endogène, ce qui permet, en particulier, de représenter l'effet de la substitution terre-engrais sur les usages des sols, compte tenu de scénarios exogènes de prix des intrants chimiques.

A l'aide de ce modèle, l'influence de la mondialisation sur l'agriculture est ensuite étudiée au travers du prisme des régimes alimentaires. A partir de trois scénarios de consommation alimentaire représentatifs, l'analyse démontre l'importance de la con-

vergence des régimes alimentaires comme facteur de tensions sur les usages des sols. Nos résultats révèlent qu'une convergence de l'ensemble du monde sur le régime alimentaire des Etats-Unis d'ici 2050 ne serait pas possible avec les tendances actuelles en matières d'expansion agricole. Les interactions entre le scénario alimentaire et les autres politiques affectant les usages des sols – soutien aux biocarburants et réduction de la déforestation – sont aussi mises en lumière, et certaines options permettant de réduire les tensions sur la ressource foncière testées.

Dans un dernier chapitre, deux perspectives de développement du modèle sont présentées afin d'analyser la question du changement climatique. Elles concernent en premier lieu le couplage avec Imaclim-R, dont l'objectif est d'intégrer une valeur cohérente de la rente foncière dans le prix agricole et les courbes d'offre de biomasse énergie. Il s'agit également d'inclure dans le Nexus Land-Use les variations de rendement des cultures simulées par le modèle de végétation ORCHIDEE sous un scénario de changement climatique. Sur ce dernier point, les premiers résultats montrent que le changement climatique conduirait à une relocalisation partielle de la production agricole des pays du Sud (Afrique, Amérique Latine) vers les pays du Nord (principalement Canada et Russie).

Summary

In a context of future tensions on the land resource, the objective of this thesis is to study the impact of global drivers, which are globalisation and climate change, on agriculture and land-use. To conduct this study, a new global land-use model, called "Nexus Land-Use", is developed, to allow for a consistent vision of the socio-biospheric system.

Existing land-use models are firstly reviewed, with the objective of assessing their capacity to estimate indirect land-use changes (ILUC). Because they result from international exchanges, ILUC can be viewed as characteristic symptoms of the influence of global drivers. Their estimation is a challenge for modellers as they require an integrated vision of the agricultural system, incorporating at the global scale a representation of both the supply- and demand-side. In spite of significant progress in the modelling of the land supply and the bioenergy sector, existing models do not manage yet to provide a robust assessment of ILUC, due especially to divergences on the price-elasticity of agricultural yields and food demand.

To meet the challenge of modelling global drivers, this thesis presents the Nexus Land-Use model. Based on a representation of agricultural intensification mechanisms, its basic characteristics are to combine economics and biophysics into a single modelling framework and to represent multi-scale effects by incorporating local heterogeneity into a global architecture. The specificity of the model is also to endogenously calculate the land rent, which makes it possible, with exogenous scenarios of chemical inputs, to model the land-fertiliser substitution and its effect on land-use.

With this modelling framework, the influence of globalisation on agriculture is studied through the lens of the food diets. Using three representative food scenarios, we show the critical role of diet convergence as driver of tensions on land-use. Our results reveal that a global convergence towards US diet to 2050 is not feasible with ongoing trends of agricultural expansion. Interactions between food scenarios and other land-use policies – support to biofuel production and reduction of deforestation

– are enlightened, and some options for mitigating tensions on land-use are tested.

Two prospects for the model development are finally presented to analyse the influence of climate change on land-use. The first one is the coupling to Imaclim-R with the aim of incorporating consistent values of the land rent into the agricultural price and the biomass supply curves. The second prospect is to include in the Nexus Land-Use crop yields variations simulated by the vegetation model ORCHIDEE under a climate change scenario. On this latter point, first results show that climate change induces a partial relocation of agricultural production from Southern regions – Africa and Latin America – to Northern ones, mainly Canada and Former Soviet Union.

Contents

List of Figures

List of Tables

Introduction

In the coming decades, patterns of agriculture and land-use are expected to be of increasing concern across societies. Growing demand for food and biomass-based energy, spurred by rapid demographic evolutions and depleting fossil energy resources, is likely to generate economic and social tensions, as was observed during the 2008 food crisis, whose intensity will heavily depend on the variations of agricultural productivity. At the same time, agriculture and land-use will be a central element in anthropogenic environmental changes. Historically the primary factor of human impacts on the environment, they are today a major contributor to global climate warming along CO_2 emissions from deforestation, decay of biomass and peat fire, and CH_4 and NO_2 emissions, which largely result from agricultural activities, accounting globally for around 40% of global greenhouse gas emissions (GHG) (IPCC, 2007)[1]. Climate change mitigation should therefore rely in large part on the agricultural sector. In addition to a change in practices, large areas of land will have to be preserved for carbon storage in soil and plant in order to reach the lowest targets in terms of greenhouse gas concentration.

This converging demand for land spurs competition for land-use, implying trade offs between feeding the world, meeting energy needs and mitigating climate change. To guide the political decisions, it is essential to have insights about the possible future of agriculture and land-use under various assumptions on demand and production. This enterprise is however challenging because of the diversity of the mechanisms at play. Habits, political intervention, biophysical features or economic behaviours are some of the numerous drivers of agricultural productivity and land-use changes, most of them being region-specific and interconnected via feedback effects. As a result, such work is extremely data-demanding and was hindered for

[1]Changes in land-use also affect climate at a local scale because of the role of vegetation in regulating local and regional temperatures and precipitations (Chase et al., 2000). They also directly impact biotic diversity worldwide (Sala et al., 2000) and are the primary source of soil degradation (Tolba et al., 1992).

a long time by the lack of consistent database (Hertel et al., 2009). Recent developments of global land-use data, that have been made possible by the use satellite imagery to detect land-use and land cover changes (Ramankutty et al., 2008; Fischer et al., 2000) and by advances in dynamic global vegetation modelling (e.g., Bondeau et al. (2007)), have stimulated research on global land economics, which is currently vivacious.

With the data availability, focus of land-use science moved to finding out the methods to forecast future evolutions of agriculture. Modelling based on past trends will not provide an accurate picture of the food and agricultural system because of the emergence of new drivers of land-use change. Among them, two global drivers are particularly important: socio-economic globalisation and climate change. By facilitating diffusion of technology, influencing lifestyles and disconnecting consumption and production sites, globalisation may affect demand as well as production conditions (Lambin and Meyfroidt, 2009; Searchinger et al., 2008). For its part, climate change may impact land-use both through its mitigation – necessitating larger land areas to produce biomass energy or to store carbon – or its impact on crop yield and land cover.

In this context, this thesis intends to bring light on the impact of global drivers, namely globalisation and climate change, on agriculture and land-use. In this view, this work seeks to detail the mechanisms governing intensification of agricultural productivity and to determine its reaction in response to global drivers. To conduct this study, a new world land-use model, called Nexus Land-Use, has been developed, so as to ensure that the various components of the agricultural productivity, from the decisions of farmers to the biophysical potentials, are consistently represented.

Beyond the representation of global drivers, the long-term purpose of this work is to supplement the integrated assessment models architecture (IAM), which groups together models from various disciplinary fields – from macroeconomy to climatology – to simulate the evolutions of GHG emissions in response to human activity. In this complex architecture, models that enable the dialogue between the various scientific expertises are generally missing. The Nexus Land-Use aims at filling this gap by providing variables that link economics and biophysics.

This thesis is comprised of four chapters, three research papers and a last chapter outlining future working prospects. The first chapter is devoted to a review of existing land-use models, with the objective of assessing their capacity to capture the influence of global drivers. In the recent years, this influence manifests itself in the expansion of agricultural lands indirectly triggered by the increased global demand for agrofuels through international trade and price channels (Searchinger et al., 2008). Overall, it appears that in spite of substantial progress, land-use models did not completely manage to provide a robust assessment of indirect effects. Moreover, due to the larger set of features they incorporate, their structure is increasingly complex making model inter-comparisons and evaluations more difficult.

Chapter 2 presents the modelling principles of the Nexus Land-Use. This model is designed to integrate fundamental features of land-use dynamics: a global scale, a multidisciplinary scientific basis and a flexible structure making it possible to combine food, biomass energy and forests demands. In addition, particular attention is given to agricultural intensification mechanisms that are often viewed as key drivers to bridge conflicts over land-use. Following chapter one's diagnosis, model features are extensively described and an evaluation of its performance on a retrospective period is provided in appendix.

Chapter 3 explores the possible futures of agriculture under a globalisation process. Among the numerous and complex mechanisms by which globalisation could potentially impact the food and agricultural system, this study concentrates on the lifestyles convergence issue. Based on the Nexus Land-Use, this chapter details the mechanisms by which shifts in food diets resulting from globalisation affect the driving forces of land-use changes.

The effects of climate change on agriculture are studied in the last chapter both from the mitigation and impacts perspective. As a minor economic sector in the industrialized countries, agriculture and land-use were often neglected in IAMs (Hertel et al., 2009). Imaclim-R (Sassi et al., 2010) is no exception to this rule. To refine the modelling of agriculture and biomass in this model, methodological guidelines for the coupling of the Nexus Land-Use to Imaclim-R are provided in this chapter. The main goal of this coupling is to account more precisely for the land constraint and to provide insights on the land rent redistribution within the economy. Finally, to evaluate the impacts of global warming on agriculture, crop yield variations simulated by the global vegetation model ORCHIDEE (Krinner, 2005) with a given emissions scenario are incorporated in the Nexus Land-Use.

Chapter 1

Assessing model capacity to capture global drivers: the indirect land-use change example

1.1 Introduction

The emergence of transboundary environmental problems and the intensification of international exchanges, linked to the globalisation of the world economy, have modified the traditional framework for analysing questions related to agriculture and ecosystems. Scale-specific analyses are no more sufficient as a modification of the production in one region can impact the whole system through international trade and price channels. In the same logic, decisions related to food, biomass energy, and forest can't be independently assessed as they can interact on each other for the use of the limited land asset.

Such statements have motivated renewed efforts to understand and model agriculture and land-use dynamics (Heistermann et al., 2006). Two major issues have also contributed to prompt studied on land-use change. First, ecosystems management became a central element of emissions scenarios as it is now admitted that the lowest objectives in terms of greenhouse gas concentration (less than 4 Wm^2) will be hardly feasible without important carbon storage in soil and plant (Vuuren et al., 2007). Secondly, the environmental impact of agrofuels has been the subject of an intense controversy in the scientific and political communities. Searchinger et al. (2008) and Fargione et al. (2008) actually demonstrated that by converting existing croplands, agrofuels contribute indirectly to the expansion of arable lands, which consequently generate important emissions of biospheric carbon. This effect is generally referred to as indirect land-use change (ILUC). From a political point of view, this conclusion is potentially of crucial importance, because including ILUC emissions in the environmental assessment of agrofuels could call into questions policies promoting agrofuels that are currently implemented in Europe and USA. From a scientific point of view, ILUC can be seen as a distinctive effect of transboundary and mutli-scale processes that represent new challenge for modelers.

In this context, the purpose of this chapter is to assess the capacity of land-use models to evaluate ILUC due to agrofuel production, with a particular focus on the solutions adopted to extend the scope of the modelled mechanisms. Section 1.2 provides an overview of the studies conducted by Searchinger et al. (2008) and Fargione et al. (2008) that have prompted an intense debate the controversy among sustainable development experts. Section 1.3 presents the various modelling innovations capable of bringing solutions to traditional land-use models deficits. Section 1.4 reviews the numerical studies initiated by the political decision-makers in Europe and in the USA to evaluate ILUC and outlines the remaining limitations of numerical models of land-use. The last section concludes.

1.2 Indirect land-use change and the controversy on the agrofuels ecological assessment

1.2.1 A First diagnosis: Searchinger and Fargione's articles

Attracted by the potential benefits of agrofuels to (1) mitigate greenhouse gases (GHG) emissions, (2) support agricultural sector and (3) secure energy supply, the large scale exploitation of biomass for energy has been implemented despite some uncertainties regarding its effective environmental impact. Thus far, the principal uncertainty concerned the emissions of nitrous oxide (Crutzen et al., 2008), resulting from fertiliser use. Studies conducted by Searchinger et al. (2008), and Fargione et al. (2008) introduced an additional potential factor of emissions related to indirect land-use change. Assuming that food demand is price inelastic, any increase in the production of biomass fuel generates a rise of crop prices and creates an incentive to extend cultivated areas. From there, the indirect land-use change concept refers to the displacement of crops (food and non-food) or pastures on uncultivated land, such as fallow or forest, resulting from the use of feedstock for agrofuels production, and generating emissions of organic carbon stored in the vegetation and the soils.

Searchinger et al. (2008) provides an estimation of the emissions from ILUC for an increase in US corn ethanol of 56 billion litters above a baseline scenario up to 2016. By using the agricultural worldwide model developed by the Food and Agricultural Policy Research Institute (FAPRI) (Devadoss et al., 1989), they calculate that this increase would divert a significant amount of cropland in the US (12.8 millions ha), and in turn trigger extension of cultivated areas, mainly in Brazil (2.8 mha), China (2.3 mha), India (2.3 mha) and in the United States themselves (2.2 mha).

Such a result leads to revalue the relevance of life cycle analysis (LCA), which are generally used to provide a comprehensive ecological assessment of agrofuels. In LCA, GHG emissions are computed at each step of the production process, from "cradle-to-grave", or in the case of agrofuels, from "field-to-tank". This tool is increasingly used by governments to assess the environmental efficiency and define targets of new regulatory policies integrating agrofuel. The European Commission Renewable Energy Sources Directive, the US Energy Independency and Security Act, the German Sustainable Biofuel Obligation Draft and the UK Renewable Transport Fuel Obligation explicitly refer to this analytical instrument. LCA are thus of prominent importance in the decision making. However they are made inside system boundaries, focusing on the environmentally relevant physical flows inside the production process, and do not capture emissions occurring outside the system boundaries via price effects, such as indirect land-use change. From this point of view, results of LCA may be biased.

Searchinger et al. (2008) evaluates the extent of this bias by comparing the emissions profile of gasoline and corn ethanol (figure 1.1). Gasoline profile is characterised by regular flows of GHG emissions stemming from refining and burning of fuel, whereas corn ethanol profile is characterised by large upfront emissions caused by land-use change (e.g, through forest clearing), followed by flows of GHG emissions lower than those from gasoline, because growing agrofuel feedstocks removes carbon dioxide from the atmosphere. In this manner, corn ethanol progressively offsets the carbon debt it has generated with upfront emissions. This profile is also studied in a second scenario, more favourable in terms of land-use change and emissions due to land conversion: yield increases allow to supply 20% of the replacement grain, emissions per hectare of converted land are only half of their initial estimate and corn ethanol reduces GHG emissions compared with gasoline of 40% thanks to improved technology. The authors calculate that corn ethanol would pay back carbon

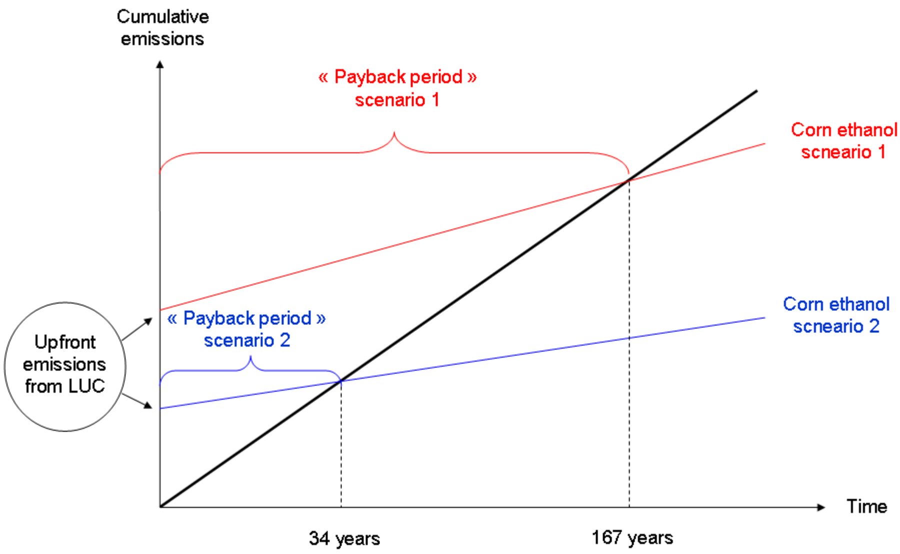

Figure 1.1: Emissions pathway of agrofuel compared to fossil fuel

emissions from land-use change in 167 years in the first scenario and 34 years in the second one.

The agrofuel carbon debt is highly dependent on the type of ecosystem that is converted. Fargione et al. (2008) calculates the amount of upfront emssions for different ecosystems in Indonesia, Malaysia, Brazil and the United-States. The results reveal that in most cases, land conversion due to agrofuel production entails large carbon debts. The conversion of peatland or rainforest to palm agrofuel is the worst case as 423 years are needed to offset land clearing emissions. In general, the carbon debt amounts at least to 17 years for first- generation agrofuel. For this reason, the authors conclude that "biofuels, if produced on converted land, could, for long periods of time, be much greater net emitters of greenhouse gases than the fossil fuels that they typically displace". On the other hand, second-generation agrofuels from perennials grown on degraded land or from waste biomass exhibit much better results in terms of carbon debt, and could therefore effectively help to mitigate GHG emissions.

On the whole, the two articles are very pessimistic about the future of the agrofuel industry. Though, their results rely on assumptions that have been highly criticised in the expert community.

1.2.2 The controversy

This first diagnosis has prompted an intense debate among sustainable development experts. The sharpest contestation came from Michael Wang and Zia Haq (Wang and Haq, 2008) and from the New Fuels Alliance[1], a non profit-organization promoting the advantages of non-petroleum fuel production and use. Their criticisms can be summed up into four axes:

- The scenario employed in the projection is unrealistic. It actually consists in an expansion in ethanol from 15 to 30 billions gallons by 2015 (56 to 111 billion liters) while the 2007 Energy Independence and Security Act established an annual corn ethanol production cap of 15 billions gallons by 2015 ;
- Estimations rely essentially on the continuation of current trends: predictions of future land-use change in the Brazil, China, India and the US are based on historical land-use change that occurred in the 1990s, not reflecting by the way the decline of deforestation rate in Brazil and the efforts made in China to convert marginal crop land into grassland and forest; yields both in the US and in the rest of the world are also assumed to increase at present trends, neglecting thus the yield response to crop price ;
- Finally, results are not corroborated by facts: corn exports have increased in 2007 though a higher corn ethanol production whereas Searchinger et al. (2008) find that U.S. corn exports sharply decline with a growing ethanol production ; observed changes in land-use offer inconclusive results about ILUC, e.g., the rate of Brazilian Amazon deforestation peaked in 2004, and has fallen since then, yielding a negative correlation of 0.53 with soybean price during the four years since 2004 (Liska and Perrin, 2009).

A response to each of this point is given in Searchinger (2008). In Searchinger (2009), the question is tackled in a different angle by underlining the fact that diverting cropland to agrofuels can only be done either by reducing food consumption, or by expanding agricultural surfaces, or by increasing yield. In the current context of alimentary and environmental tensions, the first two options are not desirable. Stimulating yield, as it has been done since the middle of the XXst century, is seen as a promising solution, but Searchinger refutes this possibility on the basis of 3 arguments: (1) only yield increases due to higher prices spurred by agrofuels must be

[1] Their letter entitled "Statement in Response to Science Articles on Biofuels" has been retrieved on 2009-06-11

taken into account. The remaining yield increase, that would occur with or without agrofuels, change the baseline, but not the results; (2) agricultural intensification usually requires high volumes of nitrogen which generates nitrous oxide, a powerful greenhouse gas; (3) yield increase potential is not unlimited, and has already been largely exploited.

On the whole, Searchinger acknowledges that some uncertainties remain, and that most detailed studies are needed, particularly on agricultural features and prices effect. For this reason and owing to the potential extent of ILUC emissions, this first diagnosis has to be validated by further modelling works, so as to properly guide agrofuel development policy.

1.3 Indirect land-use change assessment and the challenges of large scale integrated modelling

1.3.1 Specifications for ILUC modelling

Estimation of ILUC is a difficult task because such changes are not directly observable. Furthermore, ILUC theoretical functioning is complex, as they result from the interplay of various factors. Schematically, GHG emissions from ILUC can be computed by multiplying (i) the area of uncultivated land that are converted to cropland or pastures at the global scale due to increased agrofuel production by (ii) a GHG factor estimated for each hectare of land converted. However, this apparently simple calculation is challenging, as it involves four main disciplinary fields: economics, agronomy, engineering and climatology.

The size of land conversion results from the interrelation between economic behaviours and agronomic parameters. Economic behaviour determines the effect of farming an additional hectare of feedstock for agrofuels on agricultural prices, and consequently, on the cultivation of new lands. As suggested by Searchinger et al. (2008), the price-impact of agrofuel is greater when the demand for food is inelastic. Its extent is also governed by agronomic mechanisms, such as crop yield response to the incremental production of agrofuels and the substitution of agrofuel by-products for feedgrains. These two mechanisms mainly depend on the type of plants used to produce bioenergy. For example, some plants exhibit higher yield (e.g. sugar cane, sugar beet) while others provide more by-products (e.g. soybean, wheat). For this reason, it is necessary to account for these different plant types and for their specificities. Attention must also be given to the agrofuel production process – from grain (first-generation) or from lignocellulosic materials (second-generation) – that naturally crucially impacts these mechanisms. Because ILUC relates to biomass production leakage between the different regions of the world, a global representation of processes encompassing a detailed description of international trade is necessary.

The GHG factor depends on two main drivers:

- The nitrogen fertiliser used in the production process that causes emissions of nitrogen oxide (NO and NO_2), a greenhouse gas with a high warming potential;
- The type of land converted that plays a prominent role in the extent of the carbon debt. Tropical rainforests or peatland rainforests store high levels of carbon, while the conversion of marginal croplands releases lower levels of carbon into the atmosphere (Fargione et al., 2008).

These two elements vary greatly across the different regions of the world. Each region may differ in its land cover, storing more or less carbon, as well as its climate and technological itineraries, requiring more or less nitrogen fertiliser and irrigation. For this reason, international flows of agricultural goods must be tracked as precisely as possible and geographical specificities must be accounted for.

Beyond the representation of these various mechanisms, another difficulty relates to the tensions already present in the agricultural system, which may influence the effect of an increase of agrofuel production. These tensions essentially relate to arable land availability, tensions on water, and energy and fertiliser prices. Agricultural policies and global changes in food demand and diet composition, because they determine pressure on land, must also be part of the analysis. Also, because agricultural markets are not independent from the larger economy, particularly concerning energy prices, or labour and capital availability, a link to a general equilibrium representation provides a higher degree of relevance. Finally, in order to provide a relevant accounting of GHG emissions, energy and physical fluxes have to be correctly accounted for, as it is performed in life-cycle assessments (LCA).

1.3.2 Limitations of traditional land-use models

Land-use change was traditionally represented by two types of tools: economic models, mostly inspired by the Ricardian theory, and geographic models linking land cover changes to a definite number of explicative variables related to location and characteristics of land. In these approaches, each type of model was designed within the framework of particular disciplines, and economic and geographic features were quite separately represented, focusing on one aspect and depicting roughly the other.

Geographic models

Among large-scale geographic models, which are best suited to address the ILUC issue, Heistermann et al. (2006) distinguish between empirical-statistical models and rule-based models. The former category estimates the most important biogeophysical and socio-economic drivers of land-use through multiple regression methods. The CLUE model framework (Veldkamp and Fresco, 1996) is an example of a model using this method. It is composed of several modules that estimate the total area needed for different land-use types and the production of each country on the basis of the gross domestic product (GDP), population size (which is estimated using a specific module), consumption pattern and international prices. Subsequently, the area of each land-use type in a given grid cell is the result of scale-specific regression equations, where the biophysical and socio economic conditions, and the conditions at higher grid scales are the explanatory variables.

Rule-based models relies on causal chains, elaborated based on theory or expert knowledge, and linking land-use change to economic, geographic and biophysical variables. The land-use module of the Integrated Model to Assess the Global Environment (IMAGE) (A.F. Bouwman and Goldewijk, 2006) exploits this method. Following a rule accounting for crop productivity, proximity to existing agricultural land, distance to road and water, land-use types are allocated within a grid, at a 0.5 by 0.5 degree resolution, in each region of the world until the total demands, resulting from economic and demographic variables, are satisfied.

Overall, this kind of model allows for an accurate analysis of the spatial structure of land-uses, by describing the neighbourhood effect or hierarchal organization of land and by providing results at a high resolution level. However, land-use allocation is generally based on the assumption that observed spatial relations between land-use types and potential explanatory factors, representing currently active processes, remain valid in the future (Heistermann et al., 2006). Economic behaviours, implying potential modifications of allocation rules, rarely received particular attention. From this perspective, using spatially explicit models to explore future driving forces of agricultural transitions is of limited interest.

Economic models

Economic model have been used because they take into account optimisation behaviours of agents in allocating land-use. Such models can be either in partial equilibrium, considering only a subset of markets, where the remaining markets are parameterised or in general equilibrium, where all markets are explicitly modelled and are assumed to be in equilibrium in every time step.

Partial equilibrium models (PEM) can provide an explicit description of the agricultural sector while accounting for adjustments of land-use allocation in reaction to price signals. To do so, they generally calculate endogenous prices resulting either from supply demand equilibrium – see, e.g. FASOM (Adams et al., 1996), AGLINK (Adenauer, 2008), AGLU (Sands and Leimbach, 2003) or IMPACT (Ryan, 2003) - or from the effect of policy instruments, as in the ESIM model (Banse et al., 2007). Then, they determine the reaction of agents to prices in two ways: by maximising consumer and producer surpluses (FASOM, AGLU) or by solving a system of behavioural equations, relying on elasticity parameters and response functions linking crop yields, cultivated areas and food demand to prices (ESIM, AGLINK, and IMPACT).

This detailed representation allows for a great flexibility in modelling the impact on agriculture of structural variations, but it lacks coherence with respect to the rest of the economy. The computable general equilibrium model (CGE) can include additional details at the macroeconomic level by connecting agricultural markets to the rest of the economy. This provides a more relevant representation of intensification possibilities in the agricultural sector by computing labour and capital scarcity costs, as well as employment opportunities in other sectors. Macroeconomic closure is also of great interest to describe features that are closely related to energy markets, such as agrofuel production or exploitation costs (fermentation, machines...). Golub et al. (2010) finally stress the importance of general equilibrium insights to represent the by-products channel.

However, the integration of agrofuels in CGE presents two major difficulties. First, in the classic CGE representation, land is modelled as homogeneous and perfectly mobile production factor. Hence, any increase in demand for land for one specific use (e.g., crop or forestry) is met as long as land remains, but without consideration of their adequacy for the intended use. This assumption tends to overestimate the potential for heterogeneous land to move across uses, or, in an equivalent formulation, the land supply elasticity. Second, unlike macro econometric models, CGEs are not estimated, but calibrated using a social accounting matrix (SAM). A SAM is a balanced matrix that summarises all economic transactions taking place between different actors of the economy in a given period (typically one year). It is assumed that a SAM of a certain year represents an equilibrium of the economy and that the model is calibrated in such a way that the SAM is a result of the optimising behaviour of firms and consumers in the model. These SAMs are generally provided by the Global Trade Analysis Project (GTAP), but with regards to agrofuels, the data are not as precise as for the other sectors for two reasons. First, they are not represented explicitly in the SAMs, but aggregated with other sectors (e.g., fossil fuels) ; second, bioenergy production was until recently not widespread, and was primarily driven by a variety of governmental supports that are not well represented in the SAMs (Kretschmer and Peterson, 2010). For these reasons, these matrices do not give the appropriate information from which realistic agrofuel trends could be projected, and as such, they cannot be used for the study of ILUC.

1.3.3 Solutions to meet ILUC modelling challenges: towards integrated land-use models

Representing agrofuel in CGE

To solve the problem of misrepresentation of agrofuels, the MIT Emissions Prediction and Policy Analysis (EPPA), a recursive-dynamic multi-regional CGE model, uses an innovative methodology for incorporating biomass production (Reilly and Paltsev, 2008; Melillo et al., 2009). Based on the GTAP dataset, EPPA uses additional data for greenhouse gas and air pollutant emissions based on EPA inventory and projects. The GTAP data are further disaggregated to include latent technology, i.e., energy supply technologies that exist but are not active in the base year of the model, generally because they are not yet fully profitable (e.g., second-generation agrofuel). Two technologies that use biomass are introduced: electricity production from biomass and liquid fuel production from biomass. They are described by their cost structure (composed of capital, labour, land and intermediate inputs from other industries), and their competitiveness level with existing technologies - endogenously computed by the model - determines their market share.

Agrofuels are represented in the DART model (Kretschmer et al., 2008) using a comparable methodology. This model is a recursive dynamic CGE model, solving a sequence of static one-period equilibria for future time periods connected through capital accumulation and relying on GTAP 6. In this database, the refined oil products category has been disaggregated into motor gasoline and motor diesel to better account for the substitution possibilities between these two products and agrofuels (Kretschmer and Peterson, 2010). Corn production has also been separated from the "cereal grains neglected" category because corn is an important feedstock for the production of bioethanol. Bioenergy technologies are modelled as latent technology. As it is performed in Reilly and Paltsev (2008), technologies are described through their cost structure, including feedstock, electricity, and a value-added composite of capital and labour. Mark-ups are also added to account for the difference between production and prices. This methodology allows for a fairly realistic representation of the agrofuel sector but can be problematic as the technologies being only latent, there are few exchanges at the calibration year. For this reason, the projection of future trends can only be performed using strong assumptions. For example, Kretschmer et al. (2008) assumed that bioethanol trade takes place only between Brazil and the industrialised countries and small initial shares of biodiesel exports are included in Malaysia and Indonesia, where they believe that export potentials exist.

Following an alternative solution, improvement of agrofuels representation has been brought to standard CGE model GTAP (Powell et al., 1997). In this version designed for the analysis of energy markets and environmental policies, called GTAP-E (Burniaux and Truong, 2002), the nested production structure has been modified to include a capital-energy composite factor amongst the other traditional production factors of labour, land and natural resources. This factor is further disaggregated to represent all substitution possibilities (modelled by elasticity parameters) between biomass ethanol and petroleum products.

This implicit representation of agrofuels, through the production factor, without an explicit economic sector, has rapidly been refined. In subsequent modelling experiments, the SAM has been directly disaggregated to add new bioenergy sectors. Using International Energy Agency sources, the GTAP-BIO model (Taheripour et al., 2007) introduces three new commodities (ethanol from food grains, ethanol from sugarcane and biodiesel from oilseeds) into the GTAP database.

The Mirage model (Decreux and Valin, 2007), developed at CEPII for trade policy analysis, was also modified to explicitly address agrofuels issues and their consequences on land-use change (Bouet et al., 2009). Like the EPPA model, MIRAGE is a general equilibrium model relying on the GTAP database. From this database, six new sectors were added: the liquid agrofuel sectors (ethanol and biodiesel), the major feedstocks sector (maize, oilseeds used for biodiesel), the fertiliser sector, and the transport fuels sector.

CGE have also been refined to account for the use of by-products. In Taheripour et al. (2008), the GTAP-E model is modified to incorporate the possibility of producing multiple products. Hence, the grain ethanol and biodiesel industries can produce both main- and by-products (dried distillers grains with solubles for ethanol and soy and rapeseed meals for biodiesel), the latter goods being substitutes for feed grains in the livestock industry. Trade offs between main- and by-products are represented in the supply and demand side, respectively, using constant elasticity of transformation and constant elasticity of substitution. By comparing model outputs with and without by-products, Taheripour et al. show that their incorporation into GTAP-E significantly reduces the impact of agrofuel production on agricultural production and prices. The MIRAGE model was also modified to account for by-products from ethanol and biodiesel production but, in contrast to GTAP-E, they are represented as a fixed proportion of production.

Improving land supply representation in CGE

As mentioned in section 1.3.2, considering an homogenous and perfectible mobile land factor prevents accurate representation of land supply. To overcome this issue, CGE models have extensively used agro-ecological zoning (AEZ). This method consists of disaggregating a parcel of land into smaller units according to its agro-ecological characteristics, such as moisture and temperature regimes and soil type (Batjes et al., 1997). The use of AEZ data by CGE has been facilitated by its integration in the GTAP database. The database now includes 18 AEZs, covering six different lengths of growing period spread over three different climatic zones (tropical, temperate and boreal). Land-use activities include crop production, livestock raising, and forestry. This extension of the standard GTAP database permits a better evaluation of the potential for shifting land-use amongst different activities (Lee et al., 2005).

Golub et al. (2008) describe the integration of this extended database in the recursive-dynamic framework of the GTAP model and its advantage for representing land supply mechanisms. The land rent is firstly disaggregated in each region across 6 of the 18 AEZs and for 3 agricultural activities (crops, ruminants and forestry). Then, the elasticity of land supply for each activity is computed based on these land rent shares. Finally, the mobility of land across uses within an AEZ is constrained via a constant elasticity of transformation frontier.

Other CGE models, such as MIRAGE, also use the GTAP-AEZ database. In its modified version, land-use change arises from two effects: substitution, which involves the modification of crops distribution on existing arable land, and extension, which involves the conversion of non-arable lands (forests, savannah) into arable lands. The substitution effect results from the optimisation behaviour of producers, computed for each AEZ, while the extension effect is determined from an exogenous land evolution trend based on historical data, cropland prices and the elasticity of cropland extension.

The LEITAP model uses an alternative method to improve the representation of land supply (Eickhout et al., 2008; Verburg et al., 2009). This general equilibrium model is an extended version of GTAP that includes an enhanced representation of the land and agricultural markets. For example, some key features of the Common Agricultural Policy are introduced (e.g., agricultural quota). More fundamentally, LEITAP incorporates land supply curves computed by the Terrestrial Vegetation Model (TVM) of IMAGE on a 0.5 degree resolution. These curves are a function of land rental cost and are parameterised by price elasticity of land supply calibrated on data from the IMAGE model. Land supply functions are such that if land is abundant (resp. scarce), any increase in demand for agricultural land will lead to rather large (resp. small) land conversion to agricultural use and to modest (resp. large) increases in land rents.

Models coupling

A convenient way to overcome the problem of misrepresentation of agricultural sector specificities is to directly integrate the advantages of the various approaches (i.e., the precision of small scale models and coherence of large scale ones) into the same modelling framework. This is usually done by coupling general or partial equilibrium models with spatially explicit models that include insights on biophysical processes. In such an architecture, the dedicated model computes patterns of agricultural production and land allocation. These results are included in the economic model as exogenous parameters, and are used to update the calibration data. In turn, the economic model provides the spatially-explicit land-use model with information on new production conditions.

The goal here is to break with the segmentation that exits amongst the economic, geographic and biophysical analytic frameworks characterising traditional land-use models and to build numerical models with a strong multidisciplinary orientation. In contrast to pure CGE, which do not link economic values to physical quantities, the advantages of such an approach is to establish a consistent relation between both types of variables and to guarantee that projections will be realistic from both points of view. In addition, coupled systems allow for a relevant representation of multi-scale effects, as processes are represented at both high and small resolution.

The Model of Agricultural Production and its Impact on Environment (MAgPIE) is a distinctive example of such a multidisciplinary approach (Lotze-Campen et al., 2008). This mathematical programming model describes economic behaviour by minimising the total cost of production for a given amount of regional food energy demand, and has been designed to be coupled with the Lund–Potsdam–Jena dynamic global vegetation model (LPJmL) (Bondeau et al., 2007). In contrast with CGE using an AEZ representation, which remains a coarse description of the biophysical system, this integrated tool entails a full description of the dynamic processes linking climate and soil conditions, water availability, and plant growth at a detailed geographic scale worldwide. In addition, MAgPIE is able to endogenously represent yield and water use evolution.

A comparable multidisciplinary methodology has been undertaken in the Global Biomass Optimization Model (GLOBIOM) (Havlk et al., 2011). This model relies on the recursive dynamic structure of FASOM (see section 1.3.2 for more detail), to determine production and consumption levels, trade flows, and prices. These values are then conveyed to the Global Forestry Model (G4M), which compares the net present values of forestry and agriculture to determine land-use change decisions. Crop yields and soil organic carbon stock are extracted from the Environmental Policy Integrated Climate (EPIC) model according to 4 management systems (high input, low input, irrigated, and, subsistence). The results are finally downscaled to homogenous response units (HRU), i.e., spatial units (0.5 by 0.5 degree resolution) where data on soil, climate/weather, topography, land cover/use and crop management are assumed to be similar. This HRU concept assures consistent integration of biophysical features into the economic land-use optimisation model.

The advantages of a coupling with CGE have been demonstrated by Ronneberger et al. (2008), using the KLUM@GTAP model that combines the global agricultural land-use model KLUM and GTAP-EFL. This latter model is refinement of GTAP-E in terms of industrial and regional aggregation levels. The KLUM model allocates land into spatial units (0.5x0.5 degree grid for Europe) by maximising the expected profit per hectare under risk aversion, according to crop price and potential yield. Geographic location and biophysical heterogeneity of land is represented by using spatially explicit potential productivities, calculated by the crop growth model EPIC (Erosion Productivity Impact Calculator). Thus, contrary to the AEZ methodology, land is not classified by its differing productivity, but each spatial unit is associated with a given productivity. This provides a more precise land allocation and a more realistic representation of land transitions. For its part, GTAP-EFL provides crop prices and management induced yield. The relevance of the coupling was tested by comparing the results of the coupled system with those of each of its components taken separately. This analysis reveals significant differences between the simulations of KLUM@GTAP and of the standalone models, which according to the authors, "strongly supports the hypothesis that a purely economic, partial equilibrium analysis of land-use is biased; general equilibrium analysis is needed, taking into account spatial explicit details of biophysical aspects."

However, to bring general equilibrium insights, it is necessary to overcome some inconsistencies within the coupled system. Equations in the general equilibrium models are actually generally formulated in terms of value. In contrast, partial equilibrium models address quantities to accurately reflect biophysical features. This means that in this architecture, both models work with two separate price systems. In KLUM@GTAP, this discrepancy has great practical consequences. Notably it makes land quantity data incomparable between GTAP-EFL and KLUM. As a consequence small absolute changes in the area of other crops in KLUM translate into large absolute changes in GTAP-EFL. This problem can be solved by completely recalibrating the coupled system. This is however a complex task that can face data issues (e.g., lack of data on land prices). For this reason, Ronneberger et al. simply decrease the responsiveness of GTAP-EFL to changes in land allocation.

Inclusion of land-use models outputs in LCA

Traditional models also suffer from a relative disconnection from engineering studies. Examples in the literature of studies integrating outputs of land-use models in LCA are scarce. This disconnection between the modelling and the environmental assessment communities mainly stems from two reasons. First, LCA are typically static simulation models describing a production system without regard for production scale and time dimension, while land-use models perform a projection throughout a certain period of time with a given evolution of the production. Second, LCA usually describe the exchanges between a production system and its environment, while land-use models are best equipped to describe the expected consequences of a change of production on the environment.

In spite of these restraints, some initiatives attempt to reconcile LCA and land-use modelling approaches. From the distinction made by Rebitzer et al. (2004) between the attributional LCA, focusing on the exchanges between the production system and its environment, and the consequential LCA, which estimate the change in the environmental system resulting from a change of the production scale, the EPA has developed a new methodology for assessing agrofuel environmental impacts. This methodology is oriented towards the second definition, and links LCA and land-use models (U.S. Environmental Protection Agency, 2009). It relies on a set of numerical tools to provide a comprehensive estimate of GHG emissions:

- The GREET model quantifies emissions at each step of the agrofuel production process;
- Emissions due to land-use, exports and livestock market changes are estimated using the FASOM model. This model actually presents the advantage of covering a wide range of production possibilities and accounts for the main GHG emitted by agricultural activities;
- While FASOM predicts land-use change in the U.S. agricultural sector, FAPRI estimates land-use change in other countries due to the response of international agricultural production to changes in commodity prices and U.S. exports. These estimates are based on historic responsiveness to changes in price in other countries. Using MODIS satellite data, FAPRI also predicts the types of land that will be converted into crop land in each country, and calculates GHG emissions associated with land conversions;
- The EPA-developed Motor Vehicle Emission Simulator (MOVES) estimates vehicle tailpipe GHG emissions. It also represents the impact that greater renewable fuel use may have on the prices and quantities of other sources of energy, and the greenhouse gas emissions associated with these changes in the energy sector.

As previously mentioned, the difficulty in accounting for ILUC emissions relates to their time dependency, which does not fit with the traditional framework of LCA. To overcome this difficulty, the EPA uses the net present value for emissions as a common metric.

1.4 Models and decision-making

1.4.1 ILUC in agrofuel development policies

Most of industrialised countries have undertaken public support policies for agrofuel. Motivations behind these policies are numerous and complex, and environmental concerns and mitigation of climate change are often far from being their main considerations. In a context of rising prices of crude oil and geopolitical tensions, securing energy supply has been at centre of agrofuel support in many countries. In the USA, the Renewable Fuel Standard program (commonly known as the RFS program), setting requirements for agrofuel production until 2022, is integrated in the Clean Energy Act of 2007, which has been significantly renamed Energy Independence and Security Act (EISA). Other concerns, such as reducing import dependence of oil supplies; rural development and sustaining farm income have also been an objective of agrofuel support policies. Altogether, these various motivations have prompted the implementation of different policy measures, setting national targets for renewable energy. With the rise to power of environmental concerns, and the necessity to respect international commitments, the objective of GHG emissions reduction became more sensitive, and explicit environmental criteria were frequently added to production targets. Since some doubts have arose on the real virtues of agrofuels, national legislations now generally refer to broader concepts such as renewable fuel (in the USA), or energy from renewable sources (in the European Union), opening the field to every kind of clean energy.

In the USA, the RFS prescribed an increase of the volume of total renewable fuel from 9.0 billion gallons (Bgal) in 2008 to 36 Bgal in 2022. These targets shall be met under established eligibility criteria, including mandatory GHG reduction thresholds for the various categories of fuels. Agrofuels GHG emissions are evaluated over the full lifecycle, and compared to the lifecycle emissions of 2005 petroleum baseline fuels. Table 1.1 presents performance reduction thresholds as established by EISA. Eligibility criteria also concern land that can be used to grow agrofuel feedstocks. For example, Agricultural land must have been cleared or cultivated prior to 2007 and actively managed or fallow, and non-forested.

Table 1.1: Lifecycle GHG thresholds specified in EISA

Fuel Category	Thresholds *(% reduction from 2005 baseline)*
Renewable fuel	20%
Advanced biofuel	50%
Biomass-based diesel	50%
Cellulosic biofuel	60%

In Europe, agrofuel objectives in terms of production and sustainability are regulated through the directive on the promotion of the use of energy from renewable sources adopted by the European Parliament and the Council on 2009. This directive establishes mandatory targets for an overall 20% share of renewable energy and a 10% share of renewable energy in transport in the European Union's consumption in 2020. This formulation reveals the erosion of confidence in biomass fuel, as a previous commitment, announced by the Brussels Europe Council in March 2007, planned a mandatory 10% minimum target for the share of agrofuels in transport petrol and diesel consumption by 2020. The document also specifies sustainability criteria for agrofuels and bioliquids. A mandatory GHG reduction threshold is set and only agrofuels allowing for a GHG emissions saving of at least 35% is taken into account for the European targets for renewable energy. It is furthermore stated that biomass fuels shall not be made from raw material obtained from land with high carbon stock, namely wetland, continuously forested areas and peatlands.

Both texts mention ILUC, but using a very cautious vocabulary, and without enacting any concrete measures. They simply encourage the improvement and development of analytical tools to facilitate the inclusion of ILUC emissions into LCA (EISA) or the development of a methodology to minimise greenhouse gas emissions caused by indirect land-use change (European directive). In addition, at the instigation of these various legislations, several numerical evaluations have been undertaken with the help of the modelling tools previously described. The next sections present the main results.

1.4.2 ILUC evaluations

The U.S. environmental protection agency lifecycle analysis

Following the indications of the EISA, the U.S. environmental protection agency has developed a methodology to compute the aggregate quantity of greenhouse gas emissions related to the full fuel lifecycle, including direct emissions as well as emissions from land-use change (see section 1.3.3).

The results firstly indicate that ILUC emissions account for a significant part of first-generation agrofuels (at least 35% of the total emissions). With the shorter time period and smallest discount rate, cellulosic ethanol and waste grease biodiesel are the only fuels to respect EISA criteria. Soy-based biodiesel and corn ethanol processed in dry mill using natural gas or coal emits even more GHG than diesel and gasoline references. Due to the time profile of agrofuel emissions, a longer time period and a greater discount rate is more favourable for bioenergies. In this case, corn ethanol processed in dry mill using biomass meets the EISA criteria, and agrofuels emits generally less than gasoline and biodiesel references.

In addition to these results, a detailed evaluation of the payback period for the different types of biomass fuels is provided. Corn ethanol entails the longer payback period (33 years) while it takes only 3 years for switchgrass ethanol to offset upfront emissions. These results are therefore close to the second and most favourable scenario of Searchinger et al. where the payback period for corn ethanol lasts 34 years.

The study also provides confidence interval whose bounds correspond to the cases where all land conversion occurs on forest areas (worst case) or on grassland areas (best case). The range of this confidence appears to be quite large in some case, revealing that a high level of uncertainty remains about these results.

The European Commission Review

As required in the directive on the promotion of the use of energy from renewable sources, the Joint Research Centre - Institute of Energy of the European Commission (JRC-IE) has launched a survey involving several models (described for the majority in sections 1.3.2 1.3.2, 1.3.3 and 1.3.3). They are mainly partial equilibrium models: AGLINK-COSIMO (Adenauer, 2008), CARD (Tokgoz and Elobeid, 2006), IMPACT (Ryan, 2003) and CAPRI (Britz et al., 2007). Two general equilibrium models are also used GTAP (Powell et al., 1997) and LEITAP (Verburg et al., 2009) which integrates features from the land allocation module of the IMAGE model. In addition, a complete study has been carried out by CEPII and IFPRI, based on the general equilibirum model MIRAGE (Decreux and Valin, 2007). The upgraded version of the model, presented in section 1.3.3, has been modified to introduce a more detailed representation of biodiesel and ethanol sectors and co-products production and uses.

Specific efforts have been made to facilitate models comparison. Each model were asked to run scenarios corresponding as closely as possible to scenarios of marginal extra demand of ethanol in EU and in the USA, of biodiesel in EU and palm oil in EU[2]. Model outputs are considered to be mainly linear, i.e. area of additional cropland is strictly proportional to the demand. As a consequence, and to facilitate inter-comparisons, the results are expressed in hectares per tonne-of-oil-equivalent (toe).

In the US ethanol scenarios total ILUC ranges from 107 to 863 kHa per Mtoe. In the EU scenarios, the total estimated ILUC ranges from 223 to 743 kHa per Mtoe for ethanol, and from 242 to 1928 kHa per Mtoe for biodiesel. As a comparison, Searchinger et al. (2008) calculated that an U.S. ethanol production increase would

[2]The JRC-IE initiated an expert consultation to discuss the issue of model comparison and to recommend standard scenarios to compare. However these recommendations have been issued after research institutes already contracted scenarios in their work plans, and most of them did not have the possibility to run extra scenarios.

bring approximately 390 kha of additional land into cultivation per MJ of ethanol. Hence, despite the controversy about their modelling choices, their results are on the average of the different studies involved. This is though not sufficient to put an end to the debate, as the range of the results remains too large to provide a definite conclusion. While Searchinger et al. (2008) concluded that the environmental impact of agrofuels is rather negative due to the length of the payback period, the CEPII and IFPRI study, whose ILUC estimates constitute the lowest bound of the sample, consider that the net greenhouse gas effect of agrofuel to 2020 is positive.

1.4.3 Remaining limitations of numerical models

To explain the discrepancy between models results, Laborde and Atlass Consortium list a large panel of uncertainties surrounding ILUC estimates. Among them, the estimations of the crop yield response to food price and of the price-elasticity of demand for food appear to be of prominent importance[3].

Yield reaction to price was one of the major bone of contention in the controversy that followed the articles by Searchinger et al. and Fargione et al.. Agrofuel proponents argued that higher production of biomass fuel would lead to higher crop prices, which in turn would spur higher yield (see section 1.2.2).

However, though the literature provides evidence of a positive yield response in the long run, there is no consensus on its magnitude: estimates range from 0.22 to 0.76 for corn in the U.S. over the period 1951-1988 (Feng and Babcock, 2010). Moreover, these values cover a period too far in the past to be used in modern models and should be updated to account for structural changes that affect agriculture since the end of the eighties (e.g. growth in farm size...). There is also no consensus on the effect of a positive yield response to crop price. Feng and Babcock (2010) actually show that higher yields will not necessarily limit cropland expansion. Unless output prices sharply decrease, yield growth increases profits in a given area and prompts the cultivation of land of poorer quality. This assertion is corroborated by Keeney and Hertel (2009) who demonstrate, using a modified version of GTAP (see section 1.3.3 for more details), that yield increases allows the U.S. agricultural export sector to regain some of their competitiveness in foreign markets and may lead to more land-use.

More work is also needed to assess the evolution of food consumption in response to price. Within models, food consumption is driven by demand functions reflecting

[3]Edwards (2011) considers that most of the difference between models is due to divergent measures of the area saved (i) by the yield response to crop price and (ii) by less food consumption.

price and income elasticities. The limitations of such functions are described in Yu et al. (2003), which also propose a new type of demand function that could be advantageously generalised to other models. In typical demand systems, the price elasticity of plant food calories is assumed to be small and negative, while for animal products, it is set to be negative and greater than that of plant food. A meta-analysis of price elasticity of meat estimations confirms that it is significantly smaller than zero; the median price elasticity across the 4 142 recorded estimates is -0.77 (Gallet, 2009). However, this analysis also suggests that with a standard deviation of 1.28, such estimations are surrounded by large uncertainties.

Beyond these issues, the development of comprehensive models incorporating a large number of parameters raises the question of data quality. Well-designed models are actually not sufficient if they are based on flawed data. Meta-analysis of elasticity parameters estimations are frequent and provide interesting insights. However, evaluations or comparisons of databases are scarce, so there is little information on their effective quality.

1.5 Discussion and conclusion

Modelling indirect effects of bioenergy is a major challenge for land-use science because of its complexity and its potential influence on decision-making. In recent years, numerical models have been significantly improved to provide a comprehensive vision of the agricultural system. This has been performed by improving the representation of land supply and the agrofuel production process in general equilibrium models (e.g., GTAP, MIRAGE, DART). At the same time, modelling systems coupling partial equilibrium models with CGE (e.g., KLUM@GTAP) or economic modules with spatially explicit models (e.g., MAgPIE, GLOBIOM, LEITAP), and modelling architecture combining land-use and LCA models (e.g., FASOM/FAPRI/GREET) have been developed. Both methodologies have advantages and drawbacks. Coupled systems guarantee a coherent relation between economic values and physical quantities but lose the price consistency that characterises CGE.

Despite these efforts, numerical models do not completely provide a robust assessment of ILUC, as their results are surrounded by large confidence intervals reflecting the numerous sources of uncertainty. Among them, the yield and food demand responses to price appear to be of particular importance and need specific attention from modellers.

A precise understanding of lack of robustness of models remains elusive, as the mechanisms at play in such models are complex, and their interaction with exogenous assumptions are less explicit as they become increasingly sophisticated. A pitfall of current modelling practices is that numerical tools become a black box. For this reason, transparency and simplicity should be privileged as much as possible. Additionally, the great variety of parameters used in the models makes inter-comparison more difficult. For this reason, each model should provide an extensive description of its methodology and assumptions, along with a description of its strengths and limitations. From there, meta-analysis and model inter-comparisons could be useful to understand models divergence and to guide the political decisions. Finally, in addition to evaluation of models' performance, insights on the quality of underlying database are also necessary.

More fundamentally, the role played by models in decision-making raises the question of their appropriate use. Their value added is to provide a consistent vision of the studied sector by combining complex equations and various databases. In this context, they are able to represent interconnection between mechanisms at different levels and to shed light on potential unintuitive system effects, such as indirect land-use changes. However, to build a coherent framework each model relies on a theoretical structure and on several categories of assumptions whose choice requires some subjectivity (Peace and Weyant, 2008). The diversity of approaches to modelling ILUC that were presented in this review is a stunning example. For this reason, one should not expect from models robust predictions and definite answers but rather policy assessments guaranteeing internal consistency with insights on potential unexpected effects.

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Chapter 2

The Nexus Land-Use model, an approach articulating biophysical potentials and economic dynamics to model competition for land-use

2.1 Introduction

In addition to their traditional role of feeding the world, services expected from natural ecosystems and agriculture have recently extended to broader fields, such as offering new energetic options, mitigating climate change or preserving biodiversity. This increasing demand for services from a finite system may generate tensions on natural resources. Decisions related to land-use must take several elements into consideration to restore multiple and contradictive demands. First, due to global environmental issues, such as climate change or loss of biodiversity, on the one hand, and to the intensification of international exchange on the other hand, land-use changes can no longer be considered as driven by local processes. Modifications of the land cover in one region of the world have an increasing impact on land-use changes in another region through price mechanisms, thus raising the need for global studies. Secondly, because they use the same limited assets, decisions or behavioural changes related to food, biomass energy, and forest preservation can interact and must therefore be assessed conjointly.

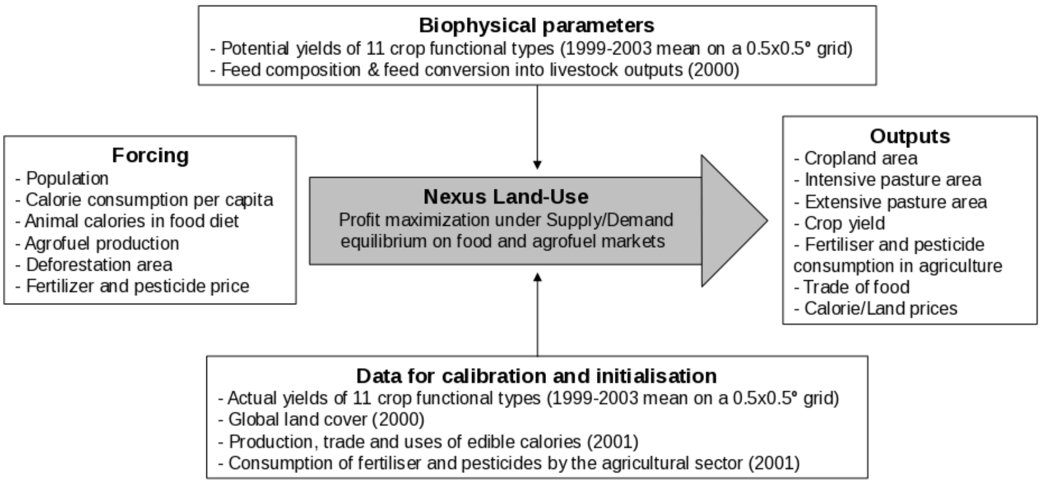

Figure 2.1: Nexus Land-Use modelling system. "Fertiliser and pesticide consumption" includes also other consumption of chemical and mineral goods.

These considerations have profoundly affected land-use modelling orientations. Originally essentially designed to evaluate local and specific issues, and characterised by the segmentation between economic and geographic approaches (Heistermann et al., 2006; Briassoulis, 2000), land-use models have progressively evolved to capture multi-scale phenomena and potential interactions with effects on land-use. To do so, two methodologies have been used. The first one consists in adapting a general equilibrium structure, mainly by improving the disaggregation of the production factors, to introduce land heterogeneity and to facilitate the calibration of the agrofuel sector (Golub et al., 2008). The second one consists in coupling partial equilibrium or computable general equilibrium (CGE) models with spatially explicit models including knowledge on biophysical processes (see e.g. Ronneberger et al. (2008)).

In contrast with the traditional approach, theses two methods demonstrate a strong multidisciplinary orientation. To provide a consistent vision of the socio-biospheric system, they rely either on elasticity parameters estimated on sample data by econometric methods (as e.g. implemented in MIRAGE, Decreux and Valin (2007)), or on an explicit description of the agricultural sector both in economic and biophysical terms as implemented in the Model of Agricultural Production and its Impact on Environment (MAgPIE, Lotze-Campen et al., 2008). This model entails a full description of the dynamic processes linking climate and soil conditions, water

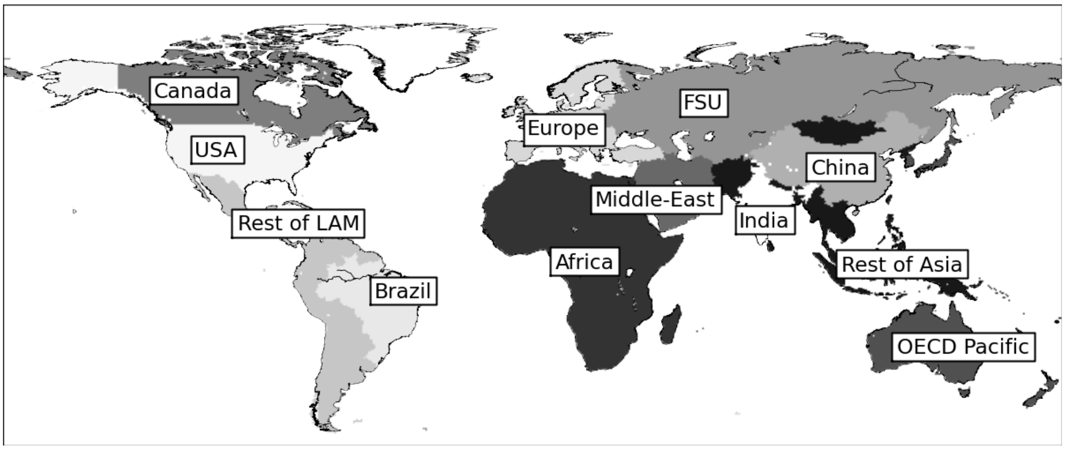

Figure 2.2: Nexus Land-Use regions. OECD Pacific includes Australia, New Zealand, Japan and South Korea. FSU stands for Former Soviet Union and Rest of LAM for Rest of Latin America

availability, and plant growth at a detailed geographic scale over the entire world through its coupling with the Lund-Postdam-Jena dynamic global vegetation model for managed Land (LPJmL, Bondeau et al., 2007).

Following those evolutions, this chapter provides a bio-economic modelling framework which ensures at the global level consistency between economic behaviours and spatial biophysical constraints in the manner of MAgPIE, and whose long term ambition is to be linked to the CGE model Imaclim-R (Crassous et al., 2006). To this end, this chapter depicts the dynamic allocation of agricultural land-use over the globe as a function of biophysical as well as economic parameters, assuming cost minimisation for farmers. Land is split into 12 regions of the globe (figure 2.2, table 2.1), and 5 land-use types: forests, croplands (2 types), and pastures (2 types). The model external drivers are the calorie consumption per capita, the share of animal products in food consumption, agrofuel consumption and evolution of forest areas (figure 2.1). Population and an index of fertiliser and pesticide prices are forced by external scenarios. In future versions of the model, some of these variables could be endogenously driven.

The principle of the model is simple. An external yearly demand of plant and animal calories in quantity must be met by adequate supply. To do so, the yield of crop plants can be increased by fertiliser and pesticide additions, up to a limit defined as “potential yield”. The demand of animal calories is converted into different types of feed, mainly: crops, grass from permanent pasture and fodder crops. The model calculates explicitly the crop yield and pastures and cropland areas, so as to minimise farmers' production costs. The evolution of these areas is determined by modelling a Ricardian production frontier between an extensive system (extensive grazing only) located on lands with the lowest potential yields and an intensive system (fertilised grasslands and croplands).

The next section details our modelling strategy and the scope of analysis. Section three describes the biophysical features of the Nexus Land-Use model. The fourth section details economical principles governing land-use changes and their parametrisations. The fifth section gives some insights on the calibration methodology. In section six, sensitivity of the area of extensive pastures to energy price and deforestation is shown. In the last section, the main hypotheses of the model are discussed.

2.2 Scope and principles of the model

2.2.1 Modelling strategy

The suitability of land for a specific agricultural use depends on its capacity to produce biomass for agriculture, which is itself determined by a large set of biophysical parameters related to soil and climate characteristics. The way farmers make use of these biophysical conditions through agronomic practices is largely driven by the socio-economic environment (evolutions of inputs or outputs prices, regulations, etc.). Although it is difficult to capture all the complex mechanisms governing farmer decisions, economic theories provide some valuable tools to account for them. They generally rely on the assumptions that agents are rational and manage their production system so as to maximize profit. This is equivalent with a cost minimisation in the agricultural sector while meeting a prescribed food demand.

In this context, the objective of the Nexus Land-Use is to combine these two dimensions – biophysics and economics – in a single coherent modelling framework. First, the representation of the production system is chosen to account for biophysical features as well as agronomic practices. This representation relies on three main components: (i) a detailed representation of the livestock production system based on the Bouwman et al. (2005) model; (ii) potential crop yields from the Lund-Postdam-Jena dynamic global vegetation model for managed Land (LPJmL, Bondeau et al., 2007); and, (iii) a biomass production function inspired by the crop yield response function to inputs (such as nitrogen fertilisers) asymptoting towards the potential yield.

Such a modelling strategy implies that among the four main production factors of the agricultural sector, land and chemical inputs with embodied energy receive particular attention while labour and capital are more roughly modelled. As a consequence, The Nexus Land-Use is better suited to dealing with land-use and energy-related issues, including or not the effect of carbon pricing, than e.g. sketching the consequences of agricultural intensification on the labour markets. Irrigation is incorporated into the model through the differentiation of potential yields on rainfed and irrigated lands (see section 2.3.1).

The economic principles governing farmer decisions are mostly inspired from the Ricardian rent theory (Ricardo, 1817). Following this theory, we consider that the poorer lands are the last to be cultivated. In the Nexus Land-Use modelling framework, the Ricardian frontier is represented as a separation between an intensive system, composed of a mosaic of crops and pastures, and an extensive system, exclusively composed of pastures, the former progressively expanding into the latter as the pressure on land rises. Hence, unlike the original Ricardian vision in which the agricultural system reacts to a growing pressure on land by expanding the size of arable lands over natural ecosystems, adjustments result from reallocations inside the boundaries of the system between intensive and extensive agriculture. This vision is consistent with the report made by Bouwman et al. (2005) that "most of the increase in meat and milk production during the past three decades has been achieved by increasing the production in mixed and industrial production systems and much less so in pastoral systems. Despite the fast increase of ruminant production by 40% in the 1970-1995 period, the global area of grassland has increased by only 4%."

In the modelling approach presented here, deforestation is not derived from economic trade offs, and is exogenously set. We actually consider, following Scouvart and Lambin (2006), that the use of forest areas could be increasingly regulated, and that their evolution could subsequently result more from political decisions than from economic ones. With the view to exploring different pathways, this assumption could be relaxed in future development of the model.

2.2.2 Modelling architecture

At the base year, a representative potential yield is computed on a $0.5° \times 0.5°$ grid from the potential yields given by the vegetation model LPJmL for 11 Crop Functional Types (CFT). Land classes grouping together grid points with the same potential yield are set up. Yield in each land class is determined by a function of chemical inputs, such as fertilisers and pesticides. This function asymptotes towards the potential yield and exhibits decreasing returns.

Following Bouwman et al. (2005), the livestock production system is divided into an extensive and an intensive system. The extensive system produces only ruminants that are fed by grazing. The intensive system includes ruminants and monogastrics. Here, ruminants are fed by a mix of grass, food crops, residues, fodder and other roughages. In both systems, grass comes from permanent pastures according to the Food and Agriculture Organisation (FAO) definition and can be grazed or cut for hay. Two types of permanent pastures are distinguished – intensive and extensive – according to the system to which they provide grass. Monogastric animals are fed with food crops, residues and fodder and animal products. Croplands are assumed to be exclusively located on the most productive lands, as well as pastures of the intensive production system. Fodder for monogastric and intensive ruminant is grown on cropland. Conversely, the extensive pastures are located on the least productive lands. This split of agricultural land does not completely fit with the data since a sizeable share of extensive pastures are located today on high-yield land classes. Therefore we consider an additional category of extensive pastures, which is called "residual pastures".

Each type of land-use – forest, cropland, intensive, extensive and residual pastures – is distributed among the land classes, giving for a land class of potential yield j the area fractions f_j^{Forest}, f_j^{crop}, f_j^{Pint}, f_j^{Pext} and f_j^{Pres}. These variables are regional as are all variables of the model except for the world calorie price.

At each time step, Nexus Land-Use calculates a global supply / demand balance from exogenous calorie consumption of food crops for agrofuel $D_{agrofuel}^{fc}$, plant food (food crops for humans) D_h^{fc}, ruminant D_h^r and monogastric products D_h^m. The total land supply for agriculture – excluding croplands not represented in LPJmL – S_{surf} is deduced from the exogenously set annual evolution of the forest area. The price of fertilisers and pesticides is also deduced from external drivers.

Given this forcing, the agricultural sector is supposed to minimise its production costs by optimizing the consumption of fertilisers and pesticides, triggering subsequent variations of crop yield, and/or by modifying the repartition between intensive and extensive livestock production systems. Regions can trade food crops with each other (Exp^{fc}/ Imp^{fc}) as well as ruminant products (Exp^r/ Imp^r) on the basis of relative prices and taking into account food sovereignty and market imperfections (the trade of monogastric products – Exp^m, Imp^m – is held constant).

In each region, the model solves a global supply demand balance of ruminant (equations 2.1-2.3) and plant food calories (equations 2.4-2.7). Demand for land D_{surf} resulting from this equilibrium must be equal to the land supply S_{surf} (equation 2.8):

$$
\begin{aligned}
Q_r &= (D_h^r + Exp^r - Imp^r)(1 + \omega_{swof}^r) && (2.1)\\
Q_{r,ext} &= D_{surf}\rho_{past}^{r,ext}\int (f_j^{Pext} + f_j^{Pres})dj && (2.2)\\
Q_{r,int} &= Q_r - Q_{r,ext} && (2.3)\\
D_{r,int}^{fc} &= Q_{r,int}\beta_{r,int}\phi_{r,int}^{fc} && (2.4)\\
D_m^{fc} &= (D_h^m + Exp^m - Imp^m)(1 + \omega_{swof}^m)\beta_m\phi_m^{fc} && (2.5)\\
D^{fc} &= D_h^{fc} + D_m^{fc} + D_{r,int}^{fc} + D_{agrofuel}^{fc} + Exp^{fc} - Imp^{fc} && (2.6)\\
Q_{other\ crop}^{fc} + D_{surf}\int f_j^{crop}\rho_j dj &= D^{fc}(1 + \omega_{swo}^{fc}) && (2.7)\\
S_{surf} &= D_{surf} && (2.8)
\end{aligned}
$$

The ruminant production Q_r is deduced from equation 2.1. Seed (s), waste (w) at the farm level and other uses (o) are added by using coefficients ω_{swo}^{fc} for food crops, ω_{swof}^r for ruminants and ω_{swof}^m for monogastrics (see section 2.5.1, "f" standing for feed use of animal products). Following our representation of the ruminant production system, Q_r results either from the extensive ruminant production system, yielding $Q_{r,ext}$, or from the intensive one, yielding $Q_{r,int}$ (equation 2.3). Production of ruminant meat and milk in the extensive system is calculated by applying the yield $\rho_{past}^{r,ext}$ to the areas of extensive and residual pastures (equation 2.2). The demand for feed to produce ruminant $D_{r,int}^{fc}$ or monogastric D_m^{fc} calories is deduced from equations 2.4 and 2.5 using the conversion factors $\beta_{r,int}$ and β_m and the feed composition factor $\phi_{r,int}^{fc}$ and ϕ_m^{fc} (see section 2.3.3). Equation 2.6 gives the composition of the demand for food crops between food use (D_h^{fc}), feed use ($D_{r,int}^{fc}$ and D_m^{fc}), agrofuel ($D_{agrofuel}^{fc}$) and trade. Equation 2.7 corresponds to the supply / demand equilibrium for food crops. A part of the cropland areas, yielding $Q_{other\ crop}^{fc}$, is not modelled by the vegetation model LPJmL. Its evolution is forced by an external scenario. The reader will find descriptions and units of main notations in table 2.9.

2.2.3 Biomass categories

Only edible biomass is accounted for, excluding fibbers, rubber, tobacco, etc. All quantities are measured according to their energy content, and expressed in kilocalories (kcal), this unit being commonly used for nutrition. This measure allows to deal with different types of biomass for human or animal consumption but it

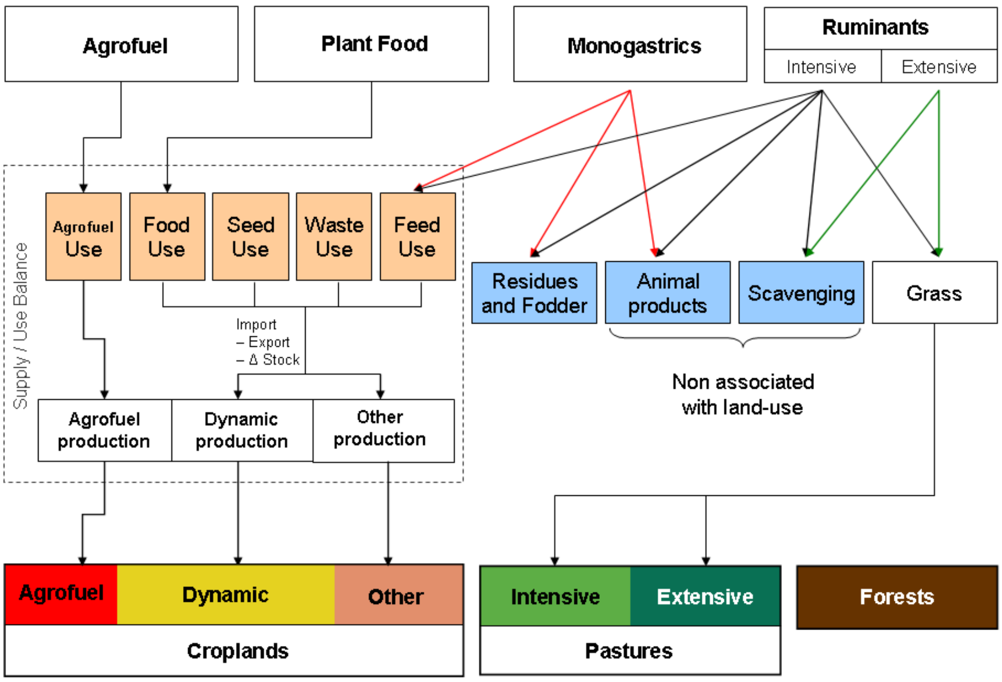

Figure 2.3: Links between food and agrofuel demand and land-use.

has some drawbacks. First, calories from different crops do not have the same economical value, e.g. the price of a cereal calorie has less value than a coffee calorie. From a nutritional point of view, the quantity of calories could be sufficient while the quantity of macronutriments (protein, lipids and carbohydrates) or micronutriments (vitamins, minerals) may be insufficient.

Four categories of agricultural products are represented (figure 2.3): first generation agrofuel, plant food for human consumption, monogastric animals (non-grazing animals, producing eggs, poultry and pork meats) and ruminant animals (producing meat and milk from cattle, sheep, goats and buffalo). Other uses of edible crop biomass correspond to non-food production such as lubricants, cosmetics (not represented in figure 2.3, see section 2.5.1 for more details). Demand for each of these four categories is forced by exogenous scenarios (figure 2.1).

Plant food for human consumption is directly assigned to food use. Animal production is modelled following Bouwman et al. (2005). According to this representation, feed for ruminants and monogastric animals are divided into five categories: (i) grass, including grazing, hay and silage grass; (ii) food crops and by-products (such as cakes); (iii) crop residues and fodder crops, including straw and bran; (iv) animal products, including whey, bone and fish meal; and, (v) scavenging, including road-side grazing, household wastes, feedstuffs from backyard farming, etc. Contrary to grass and food crops, the last two categories are not assigned to specific land-uses. The special case of the residues and fodder category is explained in section 2.3.3.

First-generation biomass fuels are represented by using biomass to agrofuel conversion factors from Johnston et al. (2009). By-products are accounted for using coefficients from BIO Intelligence Service (2010) and are considered to be substitutes for feed grains in the livestock industry. Second-generation agrofuels are not integrated yet.

The balance of supply and demand of food crop products is established on the basis of data from the global database Agribiom (Dorin, 2011). This database provides, for each country, the biomass balances in kilocalories based on the FAO annual country-level supply-utilisation accounts, ensuring consistency among the annual flows of edible biomass which are produced, traded, and consumed. In Nexus Land-Use, food crop production is modelled on the basis of crop yields computed by the vegetation model LPJmL, explicitly accounting for biophysical constraints (see section 2.3.1).

At base year 2001, crops modelled by LPJmL cover 749 Mha globally, representing 51% of the global cropland area inventoried by Ramankutty et al. (2008). Yields modelled by LPJmL are calibrated on FAO data (see section 2.3.1). The resulting production accounts for 75% of global food crops calorie production given by Agribiom (table 2.2). The remaining area/production essentially concerns sugar cane, palm oil, some roots and tubers, fruits and other vegetables. The production covered by LPJmL and its corresponding cropland area are called "dynamic." The remaining production and area are referred to as "other" and their evolutions are forced by external scenarios. Areas of permanent pastures are taken from Ramankutty et al. (2008) and forests areas from Poulter et al. (2011). The forest category includes managed and unmanaged forests. As the silvicultural sector is not modelled, no distinction between the two forest types is made. Other non-agricultural lands (deserts, ice, wetlands and built areas) are considered constant.

Except for three feed categories (residues and fodder, animal products and scavenging), each feedstock category corresponds to a given land-use. Production of fodder crop is an important land-use, but we consider that we have not enough data to incorporate this feature in the model.

The modelling of pasture areas is related to ruminant production. In the Nexus Land-Use model, ruminant products are assumed to stem either from an intensive system or from an extensive one (see section 2.3.3). In the former system, ruminants are fed with the five types of feed mentioned above, while in the latter system, they are fed exclusively by scavenging and grazing on extensive pastures. Each system is associated with its specific pastures (intensive or extensive) and with the amount of grass that is consumed per hectare. Finally, the forced evolution of forest areas determines the supply for croplands and pastures.

2.3 Modelling agricultural intensification and biophysical constraints

2.3.1 Land area classes of potential yields

Potential yields computation in LPJmL

To represent biophysical constraints affecting cultivation, yield in each region of the Nexus Land-Use is parametrised on potential crop yields, and calibrated on actual crop yields. Both values are calculated by the LPJmL vegetation model: "This model simulates biophysical and biogeochemical processes impacting productivity of the most important crops worldwide using a concept of crop functional types (CFTs). [...] CFTs are generalized and climatically adapted plant prototypes designed to capture the most widespread types of agricultural plant traits" (Bondeau et al., 2007).

LPJmL describes crop production with 11 Crop Functional Types (CFT) on a $0.5° \times 0.5°$ grid representing most of the cereals (4 CFT), oil seed crops (4 CFT), pulses, sugar beet and cassava with irrigated and rainfed variants (table 2.3). Crops not included in LPJmL CFTs (e.g. sugar cane, oil palm, fruits and vegetables, etc.) are referred to as "other crops." Climatic potential yields $y^{max}_{CFT,l}$ in tons of Fresh Matter per hectare and per year (tons FM/ha/yr) are computed by LPJmL for each of the 11 CFTs with irrigated and rainfed variants, at each grid point of global land area (l subscript), by setting management intensity parameters in LPJmL such that crop yield is maximized locally. Climatic potential yields are taken as a mean of five LPJmL simulation years between 1999 and 2003 in order to minimise the climatic bias due to interannual variability.

Management intensity is approximated in LPJmL via 3 parameters: (i) LAImax, the maximum leaf area index potentially achievable by the crops, representing general plant performance (fertilisation, pest-control), (ii) αa, a scaling factor between leaf-level photosynthesis and stand-level photosynthesis, which accounts for planting density and homogeneity of crop fields, and (iii) the harvest index HI, which determines the partitioning of accumulated biomass to the storage organs. These three parameters are assumed to be interlinked, i.e. high-yielding varieties (large HI) are used in intensively managed crop stands (Gosme et al., 2010). For details see Fader et al. (2010).

Actual yields computation in LPJmL

CFT actual yields $y^{actual}_{CFT,l}$ in tons FM/ha/yr are computed by LPJmL in the following way. First, LPJmL yield is determined, with an arbitrary intensity level of 5 for each grid point and averaged over the 1999-2003 period (intensity level is represented by the parametrisation of LAImax, αa and HI and ranges from 1 (low) to 7 (high, depending on the CFT)). Then, for each CFT and each country, a scaling coefficient is computed, such that the mean country yield matches the FAO yield over the same period. This mean country yield is calculated using annual fractional coverage of each CFT in each grid point around the year 2000 $f_{CFT,l}$ from Portmann et al. (2010). When the scaling coefficient was greater than ten, corresponding yields were set to zero considering that LPJmL failed to model these CTFs in these countries. For some CFTs (rice, maize, soybeans) on certain grid points the scaling on FAO national yield led to actual yields greater than potential ones. This may be due to the fact that the LPJmL version used here does not model multicropping (except for rice) while there may be as much as 3 harvests annually in some parts of Asia (Portmann et al., 2010). Moreover, the LPJmL CFTs may have failed to represent the dynamic of the local variety of these crops in these regions. To correct this bias, the potential yield of CFTs was set to actual yield on grid points where the actual yield was higher. This led to the addition of 1 Pkcal (10^9 Mkcal) to the potential production, corresponding to 7% of the total potential production on current croplands.

Aggregation of potential and actual yields into land area classes

One way to model food crop production is to dynamically allocate CFTs on grid points according to their expected production costs. This methodology was used by the land-use model MAgPIE where CFT choices are determined by minimizing total cost of production (Lotze-Campen et al., 2008). A drawback is that only one optimal CFT is then grown in each location. In MAgPIE this drawback is overcome by forcing rotational constraint, that is minimal and maximal shares of CFT groups (pulses, cereals, etc.) within a grid cell. In Nexus Land-Use we use a different methodology in which the potential yields of a fixed mix of CFTs are aggregated to one representative crop.

To this end, potential yields are converted in the Nexus Land-Use into calories with coefficients from Agribiom cal_{CFT} (see table 2.3). The resulting calorie yields are then combined with the annual fractional coverage of each CFT in each grid cell around the year 2000 $f_{CFT,l}$, separately for irrigated and rainfed areas, and aggregated into one representative potential yield $y_l^{max,agg}$ (in Mkcal/ha/yr). Fractional coverages are derived from maximal monthly harvested areas of each CFT at 0.5°resolution from Portmann et al. (2010). In the case of multi-cropping (more than one crop cycle within a year in the same grid point) the fractions of each CFT were adjusted to match the total cropland fraction given by Ramankutty et al. (2008) (see Fader et al. (2010) for details on CFT fractions of cells). These representative potentials yields must be interpreted as the maximum achievable yield on a grid cell assuming the CFT fractional coverage around the year 2000, and not as the maximum achievable yield on a grid cell assuming 100% coverage by the most productive CFT.

The representative potential yield on grid point l is given by:

$$y_l^{max,agg} = \frac{\sum_{CFT} y_{CFT,l}^{max} \times f_{CFT,l} \times cal_{CFT}}{\sum_{CFT} f_{CFT,l}} \tag{2.9}$$

It is displayed in figure 2.4. The representative actual yield is computed likewise and its spatial distribution is displayed in figure 2.5. In Nexus Land-Use, grid points where LPJmL crops are grown ("dynamic cropland" in the following) are aggregated into classes of iso-potential yields. From this aggregation, we define a land class as the sum of grid point area associated with a potential yield value within a specific range. For example, land class 15 includes grid points with a potential yield between 14 and 15 Mkcal/ha/yr in each region. Given this definition, the area of dynamic croplands S_j^{crop} in the land class j is:

$$S_j^{crop} = \sum_{l, \tilde{\rho}_j^{max} < y_l^{max,agg} < \tilde{\rho}_{j+1}^{max}} S_l \times \left(\sum_{CFT} f_{CFT,l} \right) \tag{2.10}$$

where $\tilde{\rho}_j^{max}$ are yields values regularly spaced every 1 Mkcal/ha/yr interval and S_l is the surface of the grid point l. The potential yield ρ_j^{max} of land class j is the

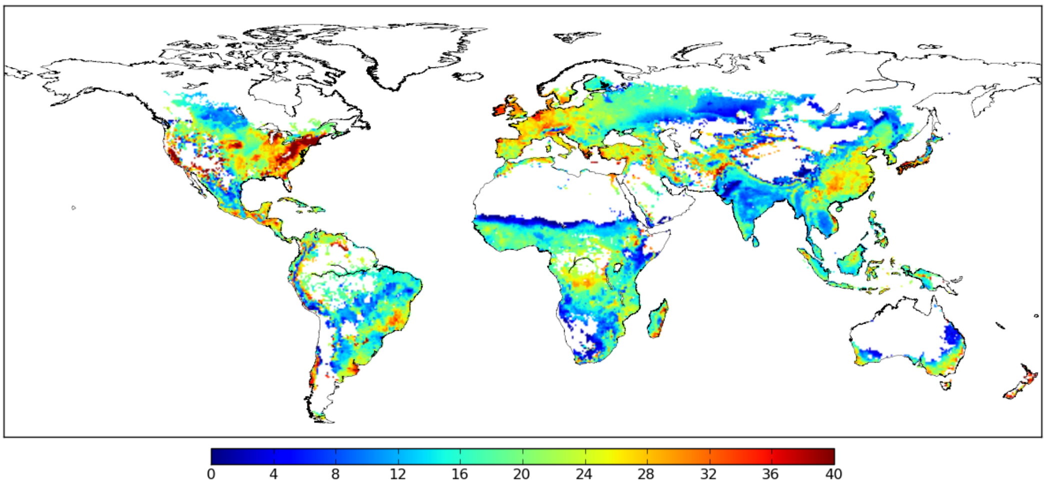

Figure 2.4: Representative potential yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

mean of the potential yield in all all grid points belonging to class j:

$$\rho_j^{max} = \frac{\sum_{l,\tilde{\rho}_j^{max} < y_l^{max,agg} < \tilde{\rho}_{j+1}^{max}} \; y_l^{max,agg} \times (\sum_{CFT} \; f_{CFT,l}) \times S_l}{S_j^{crop}} \tag{2.11}$$

Sixty land classes of potential yields are considered (from 0 to 60 Mkcal/ha/yr). Using the same method, actual yields of each land class ρ_j^{actual} are computed. We also calculate a representative potential yield on each grid point in case pasture or forests are converted to cropland (figure 2.7). To this end, an hypothetical annual fractional coverage of each CFT on each grid cell is set to the average distribution of CFTs over each country, assuming that each CFT is equally distributed in each grid cell. Only rainfed potential yields are used assuming no irrigation on newly converted croplands. In the same way as $y_l^{max,agg}$, these potential yields are the maximum achievable yields in rainfed conditions considering a crop mix over the cropland area of the grid cell representative of the country's crop mix. This rainfed hypothetical potential yield is used to distribute the area of forest, permanent pastures and other croplands within land classes according to their hypothetical yield if they are converted to dynamic croplands in our simulation (see section 2.2.3 for more details on dynamic and other croplands).

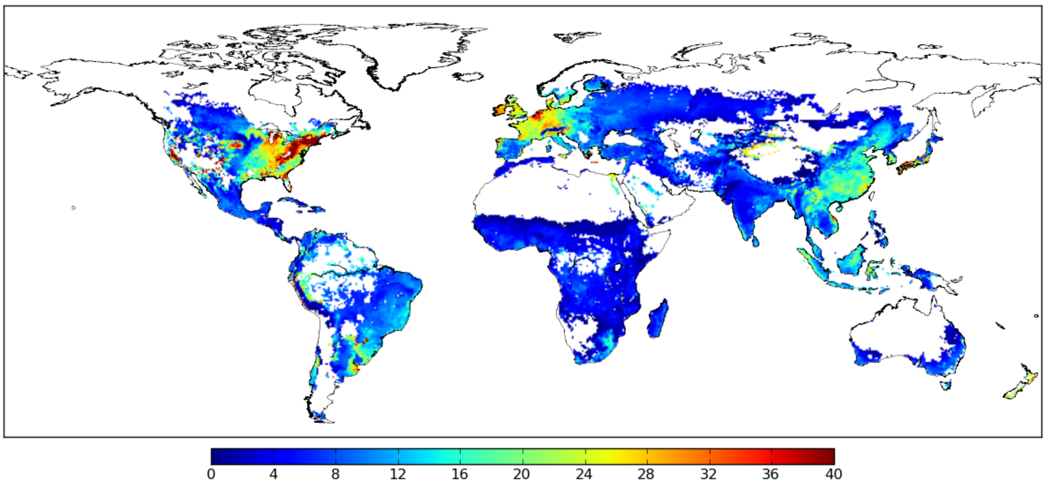

Figure 2.5: Representative actual yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

In addition to the issue related to potential yields being lower than actual yields handled above, another weakness concerns the value of potential yields that seems to be too low in equatorial regions (India, equatorial Brazil). This may be related to the lack of representation of perennial crops, which are the most productive crops in these regions (sugar cane, palm oil) (figure 2.6 and 2.7).

2.3.2 Crop production function

Factors influencing crop yields are numerous and complex. In Nexus Land-Use, yield in each land class is assumed to be a function of intermediate consumption (IC_j) from the chemical and mineral sectors, which mainly corresponds to the use of fertilisers, pesticides and mineral enrichments. This function, shown on figure 2.8, is defined by an initial slope $\frac{1}{\alpha_{IC}}$ – the same for the sixteen land classes of a region – and an asymptote equal to the potential yield of the land class ρ_j^{max} specified above. It corresponds to the yield that could be achieved with unlimited consumption of fertiliser and pesticide inputs, and reflects the saturated response of the crop to photosynthetically active radiation and climate characteristics, as well as agronomic choices such as sowing date. Water use is also accounted for as potential yields are

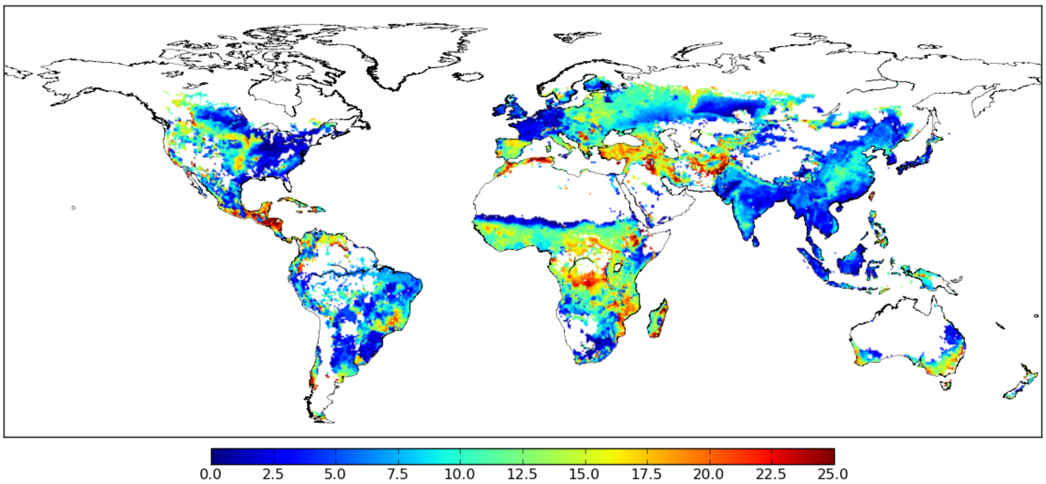

Figure 2.6: Difference between potential and actual yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

aggregates of rainfed and irrigated crops. The Nexus Land-Use production function can be considered as a form of yield response function to fertiliser application that can be simulated by crop models (Brisson et al., 2003; Godard et al., 2008), and generalized to all types of fertilisers (nitrogen, phosphorus, potassium) and to pesticides. The yield per unit of land is given by:

$$\rho_j(IC_j) = \rho_j^{max} - (\rho_j^{max} - \rho_j^{min}) \frac{\alpha_{IC}(\rho_j^{max} - \rho_j^{min})}{IC_j + \alpha_{IC}(\rho_j^{max} - \rho_j^{min})} \tag{2.12}$$

where the minimum yield ρ_j^{min} is the y-intercept, defined as the no-inputs yield. Its value is set to ten percent of the potential yield ρ_j^{max}. This choice is somewhat arbitrary but consistent with observations. Indeed, actual yields on the African continent, thought to be close to the minimum yield, are approximately equal to 10% of the potential yield (see figure 2.9). However it may lead to an underestimation in temperate regions (Thierry Doré, pers. com.).

From an economic point of view, equation 2.12 is a production function representing the technical relationship between a quantity of output (yield) and a combination of inputs (fertilisers and pesticides).

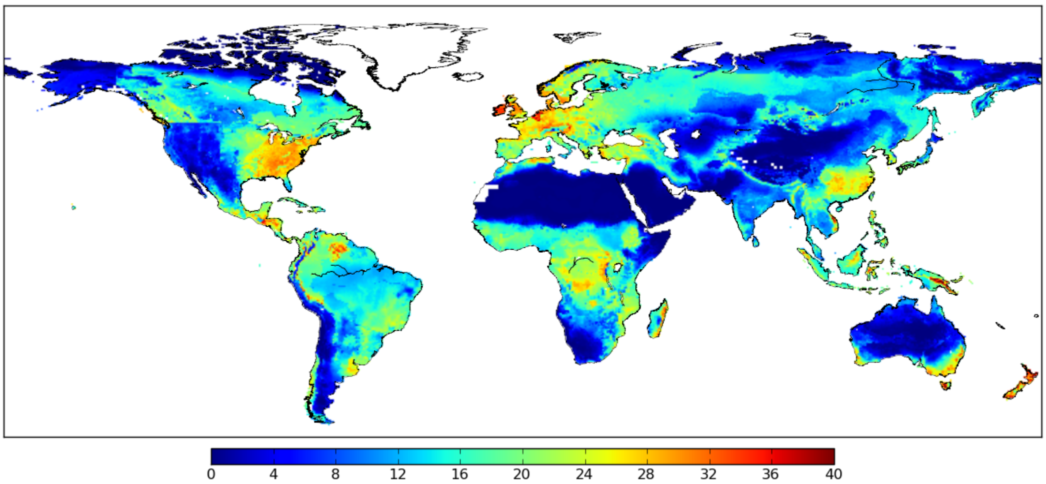

Figure 2.7: Potential yield computed with national crop repartitions in rainfed conditions (Mkcal/ha/yr) (average over the 1999-2003 period).

2.3.3 Livestock production system

The quantity and composition of feed needed to produce one unit of animal product vary greatly around the world. This is modelled by two parameters: feed conversion factors denoted β defined as the calories of feed needed to produce one calorie of animal food, and feed composition factors denoted ϕ defined as the share of each specific feed category in total feed. Feedstock categories are detailed in section 2.2.3. β and ϕ differs amongst animals and regions but also amongst production systems. The feed required by monogastrics and ruminants and its supply by pastures is represented in figure 2.10 except for animal products and scavenging because they are not associated with specific land-use. Feed conversion coefficients are quite different for meat, diary products and eggs. They have been computed considering a constant share of these different products in the ruminant and monogastric production.

Following Bouwman et al. (2005), we consider two farming systems for ruminant production: (i) the extensive system where animals are fed mainly by grazing on extensive pastures and to some extent by scavenging; and, (ii) the intensive system or mixed-landless for which animals are fed not only with grass but also with residues and fodder, food crops, animal products and by scavenging. For example, in Europe,

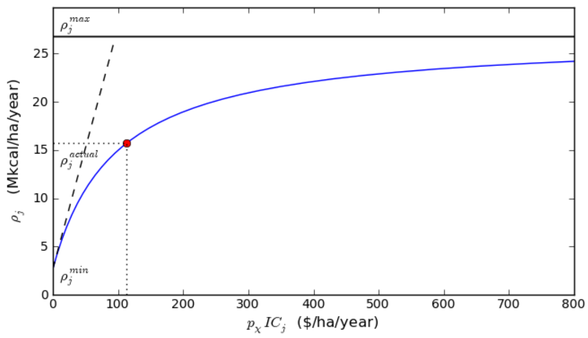

Figure 2.8: Yield in a land class as a function of chemical input consumption IC_j. ρ_j^{max}, ρ_j^{actual} and ρ_j^{min} are the potential, actual and minimum yields of the land class j. p_χ is the price index of chemical inputs.

ruminants are fed with 13% of food crops, 33% of residues and fodder crops and 53% of grass (see table 2.5). Scavenging and animal products account for a small share of the feed consumed by livestock except for scavenging in India – where it is assumed to cover half of ruminant needs (Bouwman et al., 2005).

To separate pasturelands and ruminant heads in each production system, Bouwman et al. (2005) assumed that ruminant heads belonging to the intensive system are located on a grid cell where the fraction of arable land is sufficiently high "to ensure that the production of crops for feeding animals [...] are available at short distance." Indeed, even if some food crops are imported to feed ruminants, Bouwman et al. (2005) suppose that intensive animal farming almost always takes place near croplands. Monogastrics are fed mainly with food crops, residues and fodder. They are also fed with animal products but as for intensive ruminants they account for less than 1% of the ration.

Representation of fodder crops in land-use models is usually rough. Though, fodder crops in USA, Canada and Europe account for more than 15% of the total cropland area and up to 21% in the Former Soviet Union (Monfreda et al., 2008). Furthermore, the category "residue and fodder" constitutes an important share of the intensive ruminant feed ration ranging from 15% in Canada to 34% in the Middle East. Land-use for fodder production is not modelled due to an important deficit of data. FAO statistics on fodder production are incomplete, only five crops are inventoried: alfalfa, clover, silage maize, raygrass and sorghum. Although Monfreda et al. (2008) enhanced data quality by using national inventories, statistics remain

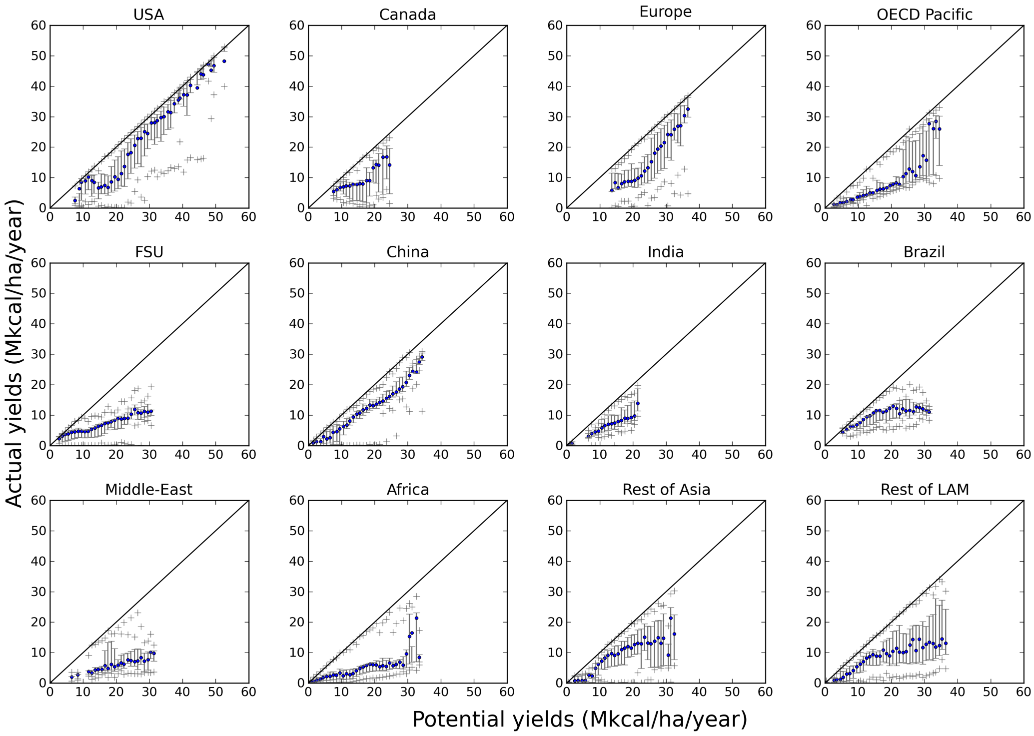

Figure 2.9: Actual yield versus potential yield of dynamic crops within each potential yield class. Crosses are minimums and maximums, whiskers go from the 20th to the 80th percentile. See figure 2.6 for a map of the difference between potential and actual yields of dynamic crops.

unreliable, in particular for Brazil and Asia. Nevertheless, several fodder crops are also included in the LPJmL CFTs (see table 2.3), and some areas for fodder production are included in the Ramankutty et al. (2008) cropland map. Therefore, no new cropland land-use is added when additional "residues and fodder" are required by animals during a simulation, only cropland areas dedicated to fodder production inventoried by the FAO at the base year are included in the model in the other cropland category.

2.3.4 Distribution of agricultural areas over land classes

Cropland, pasture and forest areas are allocated to land classes according to the representative potential yields described in section 2.3.1.

Based on the distinction between the extensive and intensive livestock produc-

Scheme 1.4 livestock production system

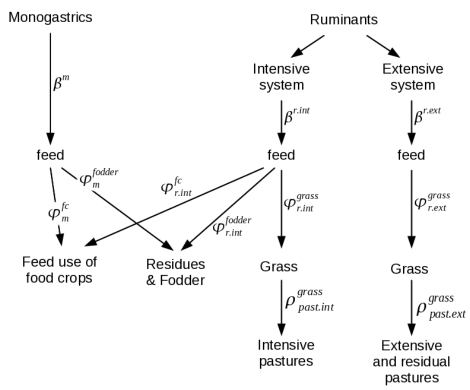

Figure 2.10: Links between animal calorie production, feed categories and pasture areas. Reading: the amount of feed required to produce one calorie of monogastric is β_m, split into a share ϕ_m^{fc} of food crops and ϕ_m^{fodder} of crop residues and fodder. Values are reported in tables 2.4, 2.5 and 2.6

tion systems, the Nexus Land-Use models the production frontier between the two systems according to economic principles inspired by the Ricardian theory. In this prospect, we consider a limit land class j_{limit} splitting agricultural lands in two parts: a first one corresponding to the intensive system where land classes have the highest potential yields and a second one corresponding to the extensive system, on lands with lower productivity (see figure 2.11). In this theoretical framework, croplands are supposed to be located on the intensive system where lands are more productive. Hence, at the base year, we assigned the least productive lands to the extensive system until the proportion of dynamic croplands become significant, the remaining part of the distribution being assigned to the intensive one. Cropland initially located in the extensive system – representing between 0 to 11% of cropland area – are assigned to the other cropland category. The limit land class separating the two systems evolves during the simulation according to a cost minimisation criterion considering calorie and energy prices in a given region.

At the calibration, the distribution of permanent pastures over land classes is split into two land-use categories: extensive pastures are located at the left of the limit land class and intensive pastures, the area of which is given by Bouwman et al. (2005), are distributed into land classes proportionally to dynamic cropland (see figures 2.12 and 2.13).

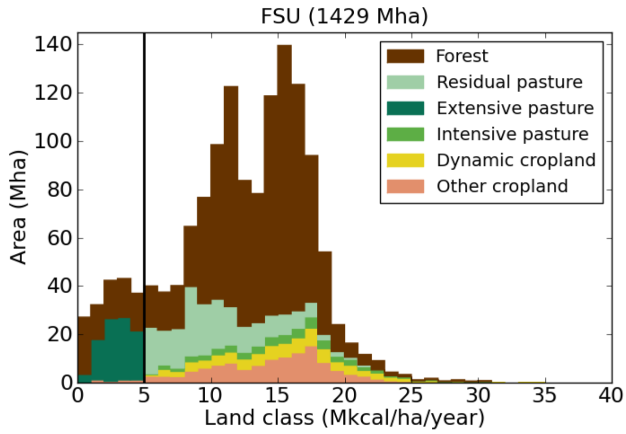

Figure 2.11: Illustration of the production frontier (limit land class j_{limit}) on the land area classes of potential yield histogram in the Former Soviet Union (black vertical bar).

In most regions, the area covered by pastures on high potential yield lands (to the right of the limit land class) is larger than the area of intensive pastures inventoried by Bouwman et al. (2005). The remaining pastures are referred to as residual pastures. Despite being located on the potential intensive side of the land distribution, we assume that these pastures have the same features as extensive ones. In the model, this use of land is assumed to be inefficient in the sense that production cost is not minimised. The residual pastures may correspond in reality to lands extensively managed because of geographic and institutional limitations (e.g. high transport cost, inadequate topography or specific land property rights, Merry et al., 2008).

2.4 Economic drivers and model dynamics

As a response to changes in the demand for agricultural biomass, with identified animal and vegetal calorie demands, the agricultural sector can adjust its production by either expanding agricultural lands over forest land or intensifying the production. Because land supply function is not implemented yet in the model, the expansion of agricultural land is constrained through prescribed deforestation scenarios in this study.

In Nexus Land-Use, the intensification of the production is driven up by two

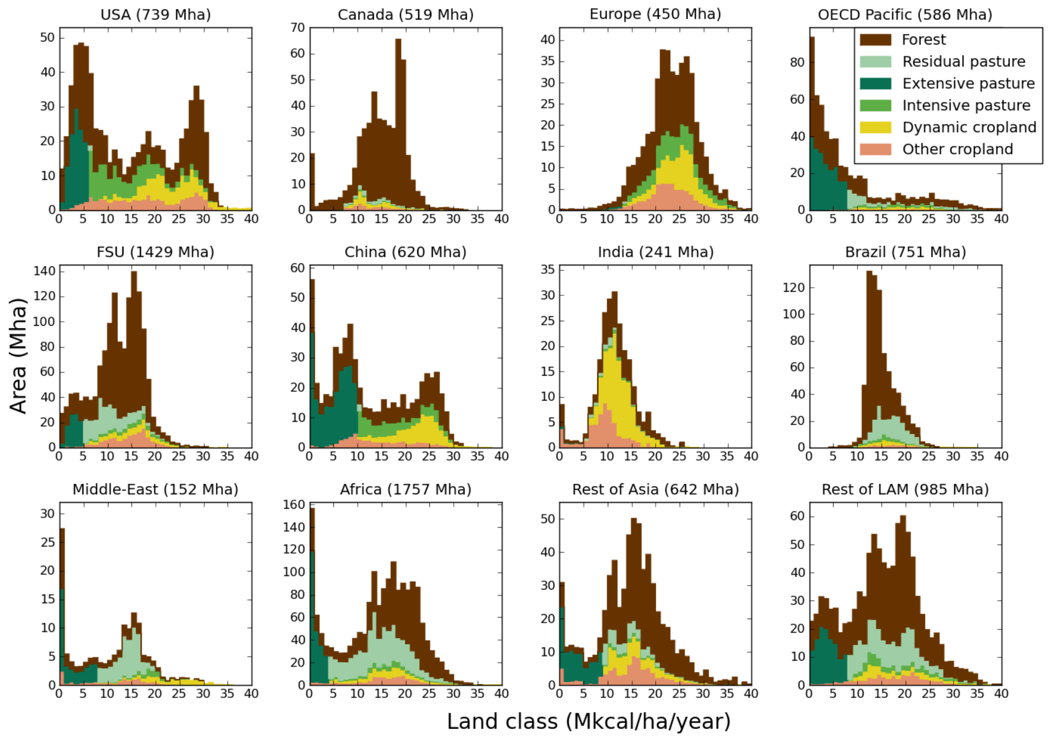

Figure 2.12: Histogram of the land area classes of potential yield in the 12 Nexus Land-Use regions at the base year.

mechanisms: (i) increase in chemical fertilisers and pesticide inputs, (ii) replacement of biomass grazed by ruminants by concentrates, residues and fodder in animal feed composition. The first mechanism comes down to an increase of crop yield, and the second to a conversion of extensive into an intensive livestock production system. The intensification level that is achieved results from the minimisation of the total production cost.

2.4.1 Crop production

Crop yield increase with agricultural inputs (fertilisers and pesticides). Trade offs between consumptions of labour and capital production factors are not represented in the model. Optimization of costs thus results from our production function choice (see section 2.3.2), which describes the biophysical dependency of yield on fertiliser and pesticide inputs. This comes down to implicitly considering that the decisions on labour and capital are independent from those on land and chemical inputs. In

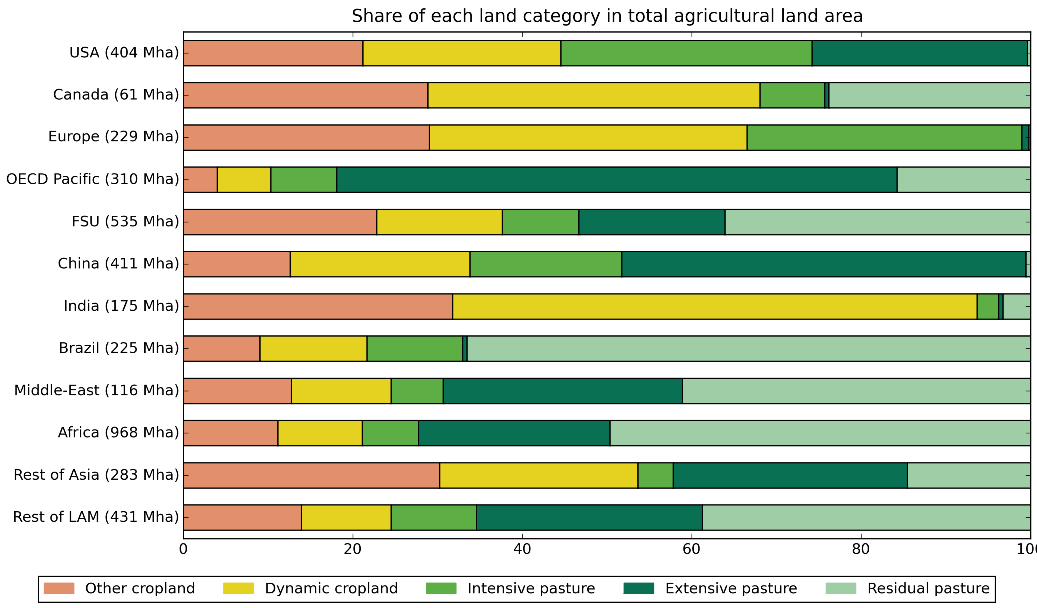

Figure 2.13: Share of different agricultural land-use types in the 12 regions of the model at the base year.

that, we assume that two choices are made, one for labour and capital, another for fertilisers, pesticides and land. In the model, we focus only on the second type of choice. As a consequence, substitutions that may exist between capital or labour and chemical inputs (e.g. herbicides reducing manual weed control) are not represented.

In each region, the annual cost function for a unit of cropland consists of:

- A fixed cost per year FC corresponding to capital, non-mobile labour, business services and energy consumption for vehicles, buildings (heating, etc.) and other on-farm operations (drying of crops, etc.).

- An aggregate cost for intermediate consumption of fertilisers and pesticides, denoted for each land class j $IC_j(\rho_j)$ and exhibiting decreasing returns. $IC_j(\rho_j)$ is defined as the inverse of the production function described in section 2.3.2 and shown in equation 2.12. It presents the following mathematical form:

$$IC_j(\rho_j) = \alpha_{IC}(\rho_j^{max} - \rho_j^{min}) \left(\frac{\rho_j^{max} - \rho_j^{min}}{\rho_j^{max} - \rho_j} - 1 \right) \tag{2.13}$$

- p_χ is the price index of fertilisers and pesticides intermediate consumption.

This function is such that $IC'_j(\rho_j) > 0$ and $IC''_j(\rho_j) \leq 0$. Calibration of the initial slope α_{IC} (in \$/Mkcal) is detailed in section 2.5.2.

2.4.2 Livestock production

The production of meat and eggs from monogastric animals is assumed to take place exclusively in the intensive type of production system. On the other hand, the production of ruminant meat and dairy takes place in either the extensive system or the intensive one. In neither system is grass directly priced, but the calorie price reflects its costs in terms of land or of fixed costs per hectare.

The area of extensive pasture on the land class j is equal to the fraction f_j^{Pext} of the total agricultural area. In the extensive system, animal feed composition consists mainly of grass (and scavenging in India) and does not rely on any food crops, fodder or residues. We assume that this grass is grown without using any fertilisers or pesticides. As explained in section 2.3.4, a share of these extensive pastures is also located on the most productive side of the distribution. On each land class j, these residual pastures cover a fraction f_j^{Pres} of the total agricultural area.

By contrast, in the intensive ruminant production system, animals are fed by food crops – in a proportion $\phi_{r,int}^{fc}$ – grass, scavenging, animal products, residues and fodder (see figure 2.10). Food crops grown for feeding ruminants are produced in association with food crops production for human use on the fractions f_j^{crop} of agricultural area and necessitate a consumption of fertilisers and pesticides $p_\chi IC_j(\rho_j)$ in \$/ha/yr.

To account for costs other than fertilisers or pesticides, we use a specific method as no database distinguishes between the intensive and extensive livestock production system costs. We define a variable FC_{tot} that also incorporates the fixed cost of crop production FC. This variable is used to compare the opportunity cost of the intensive and extensive systems and can be interpreted either as the difference between the fixed cost per hectare in the extensive and in the intensive system or as the fixed cost in the intensive system, considering that this cost is negligible in the extensive one. This cost determines the limit land class between the intensive and extensive sectors. It is calibrated to meet the base year land distribution described in section 2.3.4.

2.4.3 Minimisation program

The limit land class index between the extensive system and the intensive one is denoted j_{limit} and the upper bound of the land distribution is denoted j_{max}. Overall, the cost minimisation of the total production yields:

$$\underset{\substack{\rho_j, j_{limit}, D^{fc}_{r,int} \\ Q_{r,int}, Q_{r,ext}, D_{surf}}}{Min} \left(\int_{j_{limit}}^{j_{max}} (p_\chi IC_j(\rho_j) + FC_{tot}) f_j^{crop} dj \right) D_{surf} \tag{2.14}$$

$$Q^{fc}_{other} + \int_{j_{limit}}^{j_{max}} f_j^{crop} \rho_j dj D_{surf} = (D^{fc}_{r,int} + D^{fc}_{h+m+agro})(1 + \omega^{fc}_{swo}) \tag{2.15}$$

$$Q_r = Q_{r,int} + Q_{r,ext} \tag{2.16}$$

$$Q_{r,ext} = \left(\int_0^{j_{limit}} f_j^{Pext} dj + \int_{j_{limit}}^{j_{max}} f_j^{Pres} dj \right) \rho^{r,ext}_{past} D_{surf} \tag{2.17}$$

$$Q_{r,int} = \frac{D^{fc}_{r,int}}{\beta_{r,int} \phi^{fc}_{r,int}} \tag{2.18}$$

$$S_{surf} = D_{surf} \tag{2.19}$$

Variables are defined in section 2.2.2 and in table 2.9. As a reminder, all variables of this program are regional. Equations 2.15 to 2.19 display the constraints of the minimisation program. Equation 2.15 relates to the constraint on food crop production, $D^{fc}_{h+m+agro}$ gathering the other types of demand than feed use for ruminant animals (human, feed use for monogastrics, etc.). Equation 2.16 corresponds to the constraint on global ruminant production. Equation 2.17 is the constraint on ruminant production on extensive and residual pastures. Production of meat and milk per hectare of extensive pasture $\rho^{r,ext}_{past}$ is considered to be constant over all land classes without consideration of corresponding potential yields for crops (section 2.5.4). Equation 2.18 is the constraint on the intensive ruminant production from feed. Finally equation 2.19 provides the constraint on land availability.

The system is solved using the Lagrange multipliers method. The Lagrangian multiplier associated with the first constraint corresponds to the calorie price. The first order conditions on ρ_j is that the calorie price p_{cal} must be equal to the derivative of the function $IC_j(\rho_j)$, linking fertilising and pesticide applications to yield, times the cost of these inputs:

$$p_{cal} = p_\chi IC'_j(\rho_j) \tag{2.20}$$

The multipliers associated with the second, the third and the fourth constraint can be interpreted as the ruminant prices (global and for the extensive and intensive system). The solving of the minimisation program yields that these three multipliers are equal to each other. Hence, the price of a ruminant calorie is the same be it produced in the extensive system or in the intensive one. In the following, we denote it p_r. First order conditions on $D^{fc}_{r,int}$ leads to:

$$p_r \quad = \quad p_{cal}(1+\omega^{fc}_{swo})\beta_{r,int}\phi^{fc}_{r,int} \tag{2.21}$$

The limit between the intensive and the extensive system is given by the equality of profits in both production systems obtained through the first order conditions on j_{limit}:

$$(p_{cal}\rho_{j_{limit}} - p_{\chi}IC_{j_{limit}}(\rho_{j_{limit}}) - FC_{tot})f^{crop}_{j_{limit}} + p_r f^{Pres}_{j_{limit}}\rho^{r,ext}_{past} = p_r f^{Pext}_{j_{limit}}\rho^{r,ext}_{past} \tag{2.22}$$

This relation can be easily interpreted. The intensive livestock production system is more productive than the extensive one because its productivity is linked to crop yield. On the other hand, it is also more costly because it requires more inputs and production factors. This sets a trade off between the two systems: on high potential yield land classes, the productivity of the intensive system more than offsets its costs, making it more profitable; on the contrary, on low potential yield land classes, the extensive system will be more profitable, due to its costs and grass yield less dependent on the quality of land. The limit land class index between both systems j_{limit} is thus defined as the land (or land class in a discrete representation) over which the profit is equivalent between producing intensively or extensively, and where equation 2.22 holds.

To simplify the resolution, the fractions $f^{crop}_{j_{limit}}$, $f^{Pres}_{j_{limit}}$ and $f^{Pext}_{j_{limit}}$ in equation 2.22 are taken to be the share of each land type in its corresponding production system ($f^{Pext}_{j_{limit}}$ is thus equal to one). Indeed, it avoids the computationally very expensive sorting of profits of each land class. It is also consistent with a view in which the trade off is made between each system as a whole.

The multiplier associated with equation 2.19 can be interpreted as the shadow price of land or the land rent denoted *lambda*. The first order conditions yields the following expression:

$$\lambda \quad = \quad p_{cal}\int_{j_{limit}}^{j_{max}} f^{crop}_j \rho_j dj - (p_{\chi}IC_j(\rho_j) + FC_{tot})f^{crop} + p_r\left(\int_0^{j_{limit}} f^{Pext}_j dj + \int_{j_{limit}}^{j_{max}} f^{Pres}_j dj\right)\rho^{r,ext}_{past}$$

Following the Ricardian theory, the land rent is as a surplus paying "the original and indestructible powers of the soil" (Ricardo, 1817) that reflects the scarcity and the heterogeneous quality of land.

2.4.4 International trade

The trade of both food crops (for human as well as animal use) and ruminant calories are considered in our model. Trade of monogastrics is considered constant at its 2001 level. Indeed, it essentially takes place in regions where monogastric animals are industrially produced and where the share of residues and fodder in the feed ration ($\phi_{m,k}^{fodder}$) is small. Yet, in the Nexus Land-Use modelling framework – where residues and fodder are considered to be free – the higher the $\phi_{m,k}^{fodder}$ the lower the price will be. Hence, the price of monogastric products does not account well for the propensity of a region to export. We hypothesize that this simplification does not significantly influence the results of the model because the demand for monogastric products is converted into a demand for food crops for which trade is modelled.

The representations of trade for food crops and ruminant products rely on the same modelling principles. For this reason, we detail only the trade for food crops in this section.

Agricultural commodities can be considered to be perfect substitutes for merchandise of the same kind supplied by any other country. Therefore, the international trade is modelled by using a pool representation without any consideration of the geographic origin of goods: the global demand for imports of calories is aggregated into a single set of homogeneous goods and shared among regions according to export functions.

Demand for imports is supposed to be driven by price ratios taking into account food sovereignty considerations: the share of the domestic demand which is supplied by imports is supposed to be a growing functions of price ratios between domestic and world prices. Hence, even if domestic price happens to be higher than world price, a share of the demand remains domestically produced.

Exports shares are solely determined by relative prices, using functions reflecting the imperfect competition on the international markets of agricultural goods. As previously mentioned, the sources of imperfect competition are not related with the place of production of the goods, but to other reasons such as import barriers or export tariffs.

More specifically, imports of food crops for each region are calculated by addressing the regional demand to a pool according to a share function based on the regional calorie price p_{cal_k} and the world calorie price p_{cal}^{w} defined as follows:

$$p_{cal}^{w} = \sum ShareExp_k \times p_{cal_k} \qquad (2.23)$$

where $ShareExp_k$ is the export share of region k in the pool. It is set equal to

$\frac{\alpha_k^{exp} p_{cal_k}^{-\gamma}}{\sum_k \alpha_k^{exp} p_{cal_k}^{-\gamma}}$. Import and export functions for region k are thus given by:

$$Imp_k^{fc} = \alpha_k^{imp} \times \frac{p_{cal_k}}{p_{cal}^{w}} \times D_k^{fc} \quad (2.24)$$

$$Exp_k^{fc} = \frac{\alpha_k^{exp} p_{cal_k}^{-\gamma}}{\sum_k \alpha_k^{exp} p_{cal_k}^{-\gamma}} \times \sum_k Imp_k^{fc} \quad (2.25)$$

$$(2.26)$$

α_k^{exp} and α_k^{imp} are regional coefficients calibrated on actual import and export volumes from the Agribiom database in 2001. γ is the price-elasticity of exports. Following Hertel and Tsigas (1988), this parameter is set at 4 for plant food and at 1 for ruminant products. Exports of agricultural goods present the particular feature that they are all the more restricted than there is tension on food security. Export bans that occurred during the 2008 food crisis in several countries (India, Brazil, Kenya, etc.), or more recently in Russia after the heatwave of summer 2010, are characteristic examples (Demeke et al., 2009). To reflect such food security concerns on long term, export capacities for food crops are incorporated and defined as the gap between the potential production $\sum \rho_{j,k}^{max} f_{j,k}^{crop} S_{surf,k}$ and the domestic demand for plant food.

In accordance with the facts, this representation allows a region to simultaneously import and export a same category of goods, and countries facing different production costs may be present on the market. Another consequence of this modelling choice for international trade is related to the aggregation in calories. Indeed, the simultaneous imports and exports may also be interpreted as underlying fluxes of different commodities that we do not try to model separately.

2.4.5 Rules of land-use change

The distribution of the six land-use types over land classes (forest, residual, extensive and intensive pastures, dynamic and other croplands, see figure 2.11) is modified each year according to specific rules. This is carried out in two steps: first, the amount of forest areas is updated according the prescribed scenario. Variations of agricultural surfaces are deduced from exogenous evolutions of forest areas, neglecting phenomenons such as extension of urban areas (the sum of all land-use types is supposed to be constant throughout the projection period). The increase or decrease of forest surfaces is distributed proportionally to the size of forest area present in each land class. Finally, the supply demand equilibrium (equation 2.1 to 2.8) is calculated for each region and provide the other land-uses.

Residual pastures are considered to be an "inefficient" use of land, therefore its area in each land class get reduced as soon as the pressure on land is higher than its reference level for year 2001. The conversion speed is linearly related with the pressure on land.

As the pressure on land grows, in response to – all other things being equal – an increase of energy price and/or food crops domestic demand and/or a reduction of agricultural area (afforestation, etc.), the limit land class j_{limit} shifts towards less and less fertile land classes. Hence, extensive pastures become converted into dynamic croplands, intensive and residual pastures, according to their average area fraction on land classes of the intensive system.

The area of intensive pasture is set such as to meet the grass demand from ruminants in the intensive system:

$$\sum_j f_j^{Pint} D_{surf} \rho_{past,int}^{grass} = Q_{r,int} \beta_{r,int} \phi_{r,int}^{grass} \tag{2.27}$$

When intensive pasture area needs to be increased, land is taken from residual pastures if possible. Otherwise, land is taken from or given to dynamic cropland.

2.5 Model calibration

Unless otherwise specified, the model parameters are calibrated against agricultural and economical statistics (Agribiom, GTAP) for base year 2001 in each region (see table 2.9 for a list of calibrated parameters). This section describes the Agribiom dataset, which provides to the Nexus Land-Use data of food supply and use for the base year.

2.5.1 World supply and use of crop calories

Each year, the Nexus Land-Use model calculates a global biomass balance (figure 2.3) equalizing the annual flows of edible biomass which are produced, traded and consumed. The balance is expressed in kilocalories by aggregating many different products according to their origin (plants, ruminants, etc.), and not in tons of biomass for a range of commodities, as in most other economic models.

From a single country to the whole world, Agribiom generates synthetic and coherent estimates on the past (Dorin, 2011) and can be used to simulate and explore future possible resource-use balances of edible biomass. Its construction was initiated in 2006 with the aim of creating a tool for use in collective scenario-building such as Agrimonde (Paillard et al., 2011) and in hybrid modelling exercises such as the one presented in this chapter. The basic principle of Agribiom is to link human food diets with spaces (crops, pastures, freshwater, continental shelves, etc.) supplying edible biomass (grain, tuber, fruit, vegetable, milk, meat, fish, etc.) through resource-use balances in kilocalories that take into account trade between countries. Such balances were estimated since 1961 for five categories of edible products: plant products from croplands, products from grazing (ruminant) and non-grazing (monogastric) animals, products from freshwater or sea water. They aggregate 109 agricultural products (or group of products) edible in their primary form and for which the FAO (2010b) provides annual country-level Supply-Utilization Accounts (SUA) in metric tones (table 2.7).

The SUA volumes in tons are converted into kilocalories (kcal) via a process which uses nutritional coefficients provided by the FAO (2001) or Gebhardt et al. (2006) and assumptions regarding the processing of “primary” products (e.g. soybean) into “secondary” products (e.g. soya oil and oilcake). The output in kilocalories is similar to the supply-utilization accounts of FAO (FAO, 2010a), but without a “Processed” column on the right side:

$$Q^i_{AB} - Exp^i_{AB} + Imp^i_{AB} + \delta^i_{stock,AB} = D^i_{h,AB} + Feed^i_{AB} + Seed^i_{AB} + Waste^i_{AB} + Other^i_{AB} \quad (2.28)$$

where:

- AB subscript stands for Agribiom.
- i subscript is a category of food biomass: food crop (fc), ruminant (rumi) and monogastric (monog).
- Q is the production (kcal).
- Exp is the exports (kcal).
- Imp is the imports (kcal).
- $\delta^i_{stock,AB}$ is the stock variation (negative sign if de-stocking) (kcal).
- $D^i_{h,AB}$ is the quantity used for feeding humans (kcal).
- $Feed$ is the quantity used for feeding animals (kcal).
- $Seed$ is the quantity used for reproductive purposes (seed, eggs, etc.) (kcal).
- $Waste$ is the wasted quantity between the general available quantities (Production - Exports + Imports + ΔStocks) and their allocation to a specific use (food, feed, etc.); note that this does not include losses occurring before and during harvesting, or wastage occurring in the household (kcal).

- *Other* is the quantity used for non-food purposes: lubricants, energy, etc. (kcal).

In the Nexus model, $\delta^{i}_{stock,AB}$ is neglected. The share of seed, waste at the agricultural stage and other non-food biomass is considered to be a constant fraction of the total crop production for all the simulation. This fraction is denoted ω^{fc}_{swo} and is defined in (2.29). Corresponding coefficients for monogastrics and ruminants are ω^{m}_{swof} and ω^{r}_{swof} which also accounts for feed use (whey, bone and fish meal, etc.).

$$\omega^{fc}_{swo} = \frac{Seed^{fc}_{AB} + Waste^{fc}_{AB} + Other^{fc}_{AB}}{D^{fc}_{h,AB} + D^{fc}_{feed,AB} + Exp^{fc}_{AB} - Imp^{fc}_{AB}} \tag{2.29}$$

The consumption of crop products used as feed for livestock intensive systems is calculated using the production of monogastric and ruminant animals in the intensive system and Bouwman et al. (2005) conversion factors (see equation 2.30). The monogastric production statistics are taken from Agribiom. The ruminant production by the intensive system at the base year $Q^{2001}_{r,int}$ is diagnosed as a fraction of the total ruminant production of Agribiom according to data from Bouwman et al. (2005) on intensive grazing.

$$Q^{fc}_{feed,2001} = Q^{AB}_{m}\beta_m\phi^{fc}_{m} + Q^{2001}_{r,int}\beta_{r,int}\phi^{fc}_{r,int} \tag{2.30}$$

As previously mentioned in section 2.2.3, data from LPJmL do not cover all food crop production. The rest of the production is denoted $Q^{fc}_{other\ crop}$. Evolution of the quantity produced on the other croplands category as well as its corresponding yields are forced by an external scenario. Its production at the base year is deduced from equation 2.31, as given by:

$$Q^{fc}_{dyn\ crop} + Q^{fc}_{other\ crop} = (D^{fc}_{h,AB} + D^{fc}_{feed,2001} + Exp^{fc}_{AB} - Imp^{fc}_{AB})\omega^{fc}_{swo} \tag{2.31}$$

where $Q^{fc}_{dyn\ crop}$ is the dynamic production calculated using actual yields.

2.5.2 Calibration of the production function and the regional price of food crops calories for base year 2001

In this section, we describe the calibration of the initial slope of the production function α_{IC} and the calorie price p_{cal} at base year 2001 in each region. This calibration is done in two steps. The assumptions that the minimum yields are equal to 10% of potential yield (see section 2.3.2), implies that the yield value minimizing farmers' cost is proportional to the potential yield values over each land class.

$$\frac{\rho_j(p_{cal})}{\rho^{max}_j} = 1 - (1 - 0.1)\sqrt{\frac{\alpha_{IC} \times p_{\chi}}{p_{cal}}} \tag{2.32}$$

To make possible the calibration of the production function, yields are firstly computed so that the total production remains equal to the base year production:

$$\sum \rho_j f_j^{crop} S_{surf} = \sum \rho_j^{actual} f_j^{crop} S_{surf} \tag{2.33}$$

To assess the validity of the resulting distribution of yields over land classes, correlation coefficients between computed base year yields ρ_j and actual yields ρ_j^{actual} from LPJmL are computed for each region. They are generally above 0.8 except for Brazil where the correlation coefficient is 0.69, meaning that our linear model gives a good approximation of the reality. Then, the following system of equations is solved in p_{cal} and α_{IC}:

$$IC_j'(\rho_j) = \alpha_{IC} \left(\frac{\rho_j^{max} - \rho_j^{min}}{\rho_j^{max} - \rho_j} \right)^2 = \frac{p_{cal}}{p_\chi} \tag{2.34}$$

$$\sum_j p_\chi IC_j(\rho_j) f_j^{crop} S_{surf} = IC_\chi \tag{2.35}$$

Equation 2.34 results from the first order conditions for cost minimisation (see section 2.4.3). In equation 2.35, the sum of the intermediate consumption of each land class is set equal to the intermediate consumption from IC_χ coming from the GTAP 6 database (GTAP, 2006). IC_χ is the regional consumption of the part of the agricultural sector modelled in LPJmL from the chemical and mineral sectors (table 2.8). GTAP categories corresponding to the chemical and mineral sectors are: chemical, rubber, plastic products and mineral necessities. GTAP categories corresponding to the agricultural sector modelled in LPJmL are wheat, oil seeds, rice and cereal grain nec. Sugarbeet and sugar cane are aggregated into one single GTAP category. As sugar cane is not modelled in LPJmL, this category was removed in regions where sugar cane was believed to be in majority (India, Brazil, Rest of Asia, Rest of Latin America, Middle East, OECD pacific and Africa) and added elsewhere. The calibrated calorie price value in 2001 and the initial slope of the production function are presented in table 2.8.

2.5.3 Calibration of fixed costs per hectare

The parameter FC_{tot} is calibrated so as to ensure that at the base year the equality between costs in the intensive system and in the extensive one at the frontier j_{limit} holds (see section 2.4.3 equation 2.22). This yields:

$$FC_{tot} = p_{cal}\rho_{j_{limit}} - p_\chi IC_{j_{limit}}(\rho_{j_{limit}}) + \frac{p_r \rho_{past}^{r,ext}(f_{j_{limit}}^{Pext} - f_{j_{limit}}^{Pres})}{f_{j_{limit}}^{crop}} \tag{2.36}$$

2.5.4 Adjustments to the livestock model

In this section, we describe calculation of grass yield and modifications brought to Bouwman et al. (2005) feed conversion factor of intensive and extensive ruminants.

FAO statistics on animal products include a category called “animal fat” for which no breakdown between ruminant and monogastric animals is available. In Agribiom, this “animal fat” was entirely added to the ruminant production while Bouwman et al. (2005) ignore it. Therefore, to remain consistent with the Agribiom database we modify the feed conversion factors for intensive and extensive ruminants $\beta_{r,ext}$ and $\beta_{r,int}$ to add this production of fat. Parameters of the Nexus Land-Use livestock production model are shown on tables 2.4 and 2.5.

Potential yields apply only to dynamic cropland and are not used to calculate grass yields. In the Nexus Land-Use, the grass yields at the base year are calibrated as the ratio between grass needs and pasture areas in each livestock production system. The quantification of total permanent pasture area is highly uncertain due to the unclear distinction between rangeland and grassland pastures in national inventories (Ramankutty et al., 2008). The Ramankutty et al. (2008) data set is believed to be more reliable than the FAO statistics used by Bouwman because it combines satellite data and national inventories. For this reason, we calibrate the sum extensive and residual pastures area as the difference between total pasture area inventoried by Ramankutty et al. (2008) and the intensive pasture area from Bouwman et al. (2005). For each region of the model, the resulting extensive pasture area is combined with the total extensive ruminant grass consumption in the region, given by Bouwman et al. (2005), to obtain the yield of extensive pasture. In the same way, yield on intensive pastures is calculated by dividing the intensive ruminants grass consumption from Bouwman et al. (2005) with intensive pasture areas (table 2.6). These pastures yields are the quantity of grass grazed (as opposed to total grass grown) on a unit of land.

2.6 Example of model outputs

2.6.1 Scope, parameters and scenarios

This section provides a sensitivity analysis giving some insights on the functioning of the model. To this end, we run the Nexus Land-Use until 2050 for different evolutions of the size of arable lands and of the values of energy and chemical inputs price p_{χ}. For each of these simulations, food consumption increases following a scenario

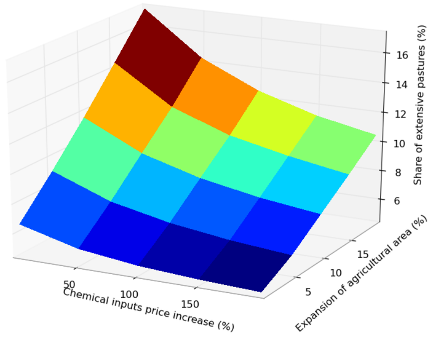

Figure 2.14: Variations of the proportion of extensive pastures in function of chemical inputs price and expansion rate of agricultural lands

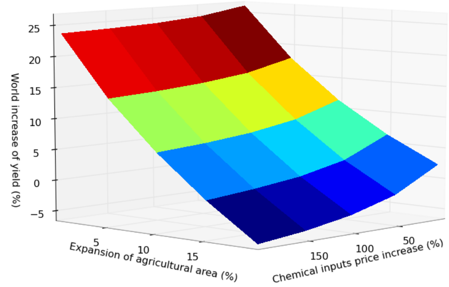

Figure 2.15: Variations of crop yields in function of chemical inputs price and expansion rate of agricultural lands

inspired by the Millennium Ecosystem Assessment scenario "Global Orchestration" (Millennium Ecosystem Assessment, 2005). Population grows according to the median scenario of the United Nations (United Nations, Department of Economic and Social affairs, Population Division, 2004) and agrofuel production is set constant at its 2001 level for the sake of simplicity. The maximal conversion speed of residual pastures is set to 20% per year. The area of the "other cropland" category and its corresponding production is fixed at its 2001 level.

In the model, adjustments to variations of production are governed by the evolutions of crop yields and of extensive pastures area. Given their critical role, we present on figure 2.14 and figure 2.15 the 2050 values of these two key drivers resulting from each simulation. The evolutions of crop yields are represented using a world crop yield defined as the mean of each regional crop yield weighted by regional cropland areas. The area of extensive pastures is computed as the share of the area of extensive pastures in the total area of agricultural lands.

To exhibit the consequences of relaxing land pressure in the most readable way, we choose to crudely apply a same rate of expansion of agricultural lands to each of the 12 regions of the model, even if in some cases this scenario is not coherent with the actual evolution. In these simulations the selected expansion of agricultural surfaces between 2001 and 2050 ranges from 0 to 20%.

The value of the fertiliser and pesticide price index p_χ is set equal to one at the base year in every regions of the model. For this sensitivity analysis, variations to 2050 range from 0% to + 200%. Here again, we aim only at exploring the consequences of hypothetical variations of p_χ on the key drivers of the model, without particular regards to the realism of the envisaged evolutions.

2.6.2 Key results

In the Nexus Land-Use, crop yields result from the trade off between land and chemical inputs prices. Hence, an increase of p_χ disadvantages the use of chemical inputs over land and generate a yield reduction *ceteris paribus*. This effect stands out clearly in figure 2.15. Conversely, as arable land becomes scarcer, its shadow costs λ increase, favouring all other things being equal the use of chemical inputs and prompting up yield increase. The form of the layer indicates that land scarcity tends to reduce the elasticity of yield with respect to p_χ, showing that as land pressure grows, the flexibility to choose yields considering chemical and energy prices diminishes. When the pressure on land is low, the elasticity of yields to p_χ is such that it brings out the non-linear form of the crop production function (see section 2.3.2). When the pressure on land peaks (at lowest rate of expansion of agricultural lands), this elasticity diminishes, revealing a smaller non-linearity. The volume of consumption of chemical inputs, also provided by the model, follows the same pattern as the yields: a doubling of p_χ induces a reduction of 4% of the 2050 chemical inputs consumption when the size of agricultural lands remains constant and a reduction of 11% with expansion of agricultural lands of 20%.

Figure 2.14 shows that the proportion of extensive pastures diminishes as p_χ rises and as the deforestation rate drops. When p_χ increases, it is actually necessary to intensify the livestock production by converting extensive pastures into crop or intensive pastures, in order to compensate the loss of production due to the fall of yield resulting from the rise of p_χ. Moreover, when the expansion of agricultural lands decreases and the arable lands become scarcer, the production must be intensified both by pushing up yields and by converting extensive pastures.

2.7 Discussion

The model presented in this chapter is at its first step of development and several paths of improvement are possible. In the current version of the model, the mix of cultivated crops is supposed to be constant over time. This implicitly accounts for agronomic choices, local preferences, cropping system (rotations) and so on. Nevertheless, this may lead to over- or under- estimation of the potential yield. For example a scenario with a high demand for animal products should trigger a shift in production resulting in an increased share of a crop like maize in the crop mix. Such a shift should feedback on the potential yield, because of the better caloric productivity of this particular crop. Given the assumption of a constant mix of cultivated crops, the Nexus Land-Use cannot account for this effect. As the crop mix is composed of relatively homogeneous crops with respect to their yield, we consider that this error is not greater than the one we would have made by computing another mix of crops disconnected from the patterns previously mentioned. In future versions of the model, this issue could be overcome by modifying the potential yield according to the projected mix of crops.

The production function could be improved in several ways. This firstly concerns the representation of capital and labour. Even if it is not the main focus of the model, exploring the consequences of the agricultural intensification on the labour market could be interesting, especially in developing countries where agricultural manpower still constitutes an important share of the working population. Some ameliorations could also be brought to model manure use, which is for the moment simply incorporated in the calibration coefficients. Indeed, an increase of animal production also means an increase in available manure which could be substitutable to industrial fertilisers and allow for a reduction of intensification costs. Several solutions are possible, the simplest would be to index the coefficients of the production function on the animal production per cultivated hectares.

The theoretical basis governing the Nexus Land-Use does not completely match the reality. Inspired by Ricardian principles, the theory states that cropland and intensive pastures should be located exclusively on the most productive lands, while the remaining lands should be occupied by extensive pastures. This tends to introduce a bias towards concentrating cropland too strongly on best lands. To mitigate this effect, we introduce "residual pastures" that belongs to the extensive system but are located on productive lands, and that can be converted into croplands or intensive pastures with varying speeds. Using a Ricardian frontier, however, makes it possible to represent the yield decrease resulting from the cultivation of lower quality lands. In comparison to other models where yield evolution is exogenously set or where the heterogeneity of land is not accurately accounted for, the simulation of yields will thus be more consistent with the actual distribution of land productivity.

At the base year, the calibration data used for cropland and pasture area (Ramankutty et al., 2008) shows that if only small amounts of cropland are located on the least productive lands, the size of pastures on higher-yield lands is sometimes significantly greater than the areas of intensive pastures reported by Bouwman et al. (2005). The gap is filled by the "residual pastures" category. Brazil appears to be the country with the largest share of residual pastures in the model (see figure 2.13). This country is characterised by some market imperfections limiting the efficient use of land, such as an opaque land market (Merry et al., 2008) and a limited access to credit by farmers (de Gouvello et al., 2010). Regions with the lowest share of residual pastures are the USA, Europe, India and Asian countries. These regions have actually been at the cutting edge of the Green Revolution, which has favoured a more efficient use of land by e.g. improving the institutional environment (creation of rural financial institutions, etc.).

Finally, agronomic representation used in the Nexus Land-Use is based on a distribution of land into land classes of potential yields which may not match reality, in part because they are based on a vegetation model, here LPJmL. As mentioned in section 2.3.1, potential yields are not correct everywhere, notably because of issues on multicropping representation, the lack of perennial crops and errors due to the LPJmL CFT approach. Also, potential yields are a theoretical construct based on many assumptions such as the variety parametrisation or photosynthetical efficiencies. More fundamentally, the Nexus Land-Use is designed within the green revolution paradigm based on the selection of varieties, use of chemical fertilisers and pesticide inputs and low labour intensive production, but ignores other promising possibilities such as agroecology (Francis et al., 2003; Wezel et al., 2009).

2.8 Conclusion

Interactions concerning food demand, biomass energy and forest at the global scale are subject to growing interest, especially regarding indirect land-use changes (Searchinger et al., 2008) and the consequences for food prices of agrofuel production and forest preservation (Baier et al., 2009; Tokgoz and Elobeid, 2006; Wise et al., 2009). This study presents a new global model approach to tackling this issue by providing a detailed representation of agricultural intensification mechanisms – which are viewed as a key driver to bridge conflicts on land-use (van Vuuren et al., 2009) – in a structure accounting for the main types of demand for biomass at the global scale.

In contrast to most land-use models, intensification is described in the Nexus Land-Use for food crops production, through an increase of chemical inputs, and for livestock production as well, through conversion of pasture into cropland and subsequent modifications of the animal feed composition. This description relies on a hybrid representation where intensification results from economic as well as biophysical processes. This methodology has several advantages. First, the integration in the Nexus Land-Use model of regional land area distributions of potential yields and the modelling of a Ricardian frontier of production make it possible to explicitly represent the variations of yield induced by the expansion of cropland on marginal lands. Secondly, technical change can be simulated both in agronomy – through a prescribed increase of potential yields – and in zootechnics – through a change of livestock production model parameters.

The Nexus Land-Use framework makes it possible to explore jointly the effect of changes in diet with respect to total calories and animal share, agrofuel production and deforestation in a context of changing energy price. Some sensitivity scenarios were explored with a special focus on the effect of future deforestation and rising energy prices on agricultural intensification. According to these results, an increase of energy price induces a yield reduction and a diminution of extensive pastures area. Reducing deforestation also decreases extensive pasture area but leads to a growing consumption of agricultural inputs. Most importantly, these results show that incorporating biophysical constraints in a land-use model generates a non-linear response of crop yield and extensive pastures area to variations of energy price and deforestation rate.

Table 2.1: Main input data for each region of the model at the base year 2001. Cropland and pasture areas are from Ramankutty et al. (2008). Forests areas from Poulter et al. (2011). Other data are from Agribiom (Dorin, 2011). Population is in millions. Diet is calorie consumption in kcal per capita and per day followed by the fraction of animal products in brackets. Consumption for seed, waste at the farm level and other consumption of food crops such as lubricants and cosmetics in kcal/cap/day. Net imports of food crops and animal products in kcal/cap/day. Food crops used as feed in kcal/cap/day (section 2.5.4). Areas are in Mha.

Regions	Population	Diet	Seed, waste	Net imports of food		Food crops
			Other	Crops	Animal	for animals
USA	311	4105 (30%)	861	-3344	-135	6939
Canada	31	4167 (30%)	1424	-7408	-435	9174
Europe	585	3875 (30%)	1053	930	-52	4248
OECD Pacific	197	2988 (20%)	364	1919	-165	2208
FSU	280	3101 (20%)	1010	138	62	2515
China	1284	3005 (17%)	598	254	19	1314
India	1060	2310 (8%)	284	34	-2	212
Brazil	177	3168 (22%)	1146	-2161	-72	2674
Middle East	146	3076 (12%)	488	2550	74	1626
Africa	826	2510 (6%)	438	636	26	458
Rest of Asia	884	2430 (8%)	502	-379	17	500
Rest of LAM	324	3067 (19%)	782	-721	94	1623
World	6106	2893 (16%)	603	-	-	1644

Table 2.1: Continued.

Regions	Area		
	Cropland	Pasture	Forest
USA	180	224	334
Canada	42	19	458
Europe	154	77	220
OECD Pacific	34	277	276
FSU	205	332	894
China	141	272	209
India	169	11	65
Brazil	50	176	526
Middle East	29	88	36
Africa	213	764	788
Rest of Asia	154	130	359
Rest of LAM	108	325	553
World	1477	2694	4721

Table 2.2: Mean of food crop production over the period 1999-2003 from Agribiom and LPJmL production according to actual yields and annual fractional coverage per grid cell CFT around the year 2000 from Fader et al. (2010). Ramankutty cropland area in the year 2000 and LPJmL cropland area around the year 2000. LPJmL cropland area and production are referred to as "dynamic" in the chapter.

	Crop production (Pkcal)		Croplands (Mha)	
Region	Agribiom	LPJmL	Ramankutty	LPJmL
USA	1.61	1.60 (99%)	180.1	94.5 (52%)
Canada	0.23	0.20 (89%)	41.5	23.8 (57%)
Europe	1.52	1.32 (87%)	153.4	86.0 (56%)
OECD Pacific	0.24	0.16 (65%)	33.8	19.5 (58%)
FSU	0.61	0.54 (88%)	203.2	79.2 (39%)
China	1.87	1.32 (71%)	140.8	87.0 (62%)
India	1.06	0.72 (68%)	168.6	108.5 (64%)
Brazil	0.53	0.31 (58%)	49.7	28.4 (57%)
Middle East	0.13	0.09 (72%)	29.0	13.7 (47%)
Africa	0.83	0.46 (56%)	212.3	96.5 (45%)
Rest of Asia	1.24	0.67 (54%)	153.3	66.1 (43%)
Rest of LAM	0.67	0.45 (67%)	107.0	45.7 (43%)
World	10.52	7.84 (75%)	1472.7	748.8 (51%)

Table 2.3: FAO and MIRCA2000 (Portmann et al., 2010) aggregates corresponding to LPJmL CFTs. Calorie content cal_{CFT} in Mkcal/tons of fresh matter from Agribiom, followed by the share of each CFT in global cropland area in percent (1493 Mha in 2000, Ramankutty et al., 2008) and in global food crops production (mean over the 1999-2003 period: 10.5 Pkcal, Agribiom).

FAO crops	MIRCA2000 crops	LPJmL CFTs	cal_{CFT}	% Area	% Production
Wheat Barley Rye Rye grass for forage and silage	wheat barley rye	wheat	3.34	17.0	22.1
Rice	rice	rice	3.6	6.7	13.6
Green corn (maize) Maize Maize for forage and silage	maize	maize	3.56	9.2	21.8
Millet Sorghum Sorghum for forage and silage	millet sorghum	millet	3.4	4.7	1.9
Beans, dry Beans, green Broad beans, dry Broad beans, green Chick peas Cow peas, dry Lentils Lupins Peas, dry Peas, green Pulses, other	pulses	field pea	3.46	4.1	2.0
Sugar beets	sugar beets	sugar beets	0.7	0.4	1.5
Cassava	cassava	cassava	1.09	1.3	2.1
Sunflower seed	sunflower	sunflower	5.7	1.3	1.3
Soybeans	soybeans	soybeans	4.16	4.6	6.1
Groundnuts	groundnuts peanuts	groundnuts	5.67	1.3	1.6
Rapeseed	rapeseed canola	rapeseed	4.94	1.5	1.6

Table 2.4: Monogastic feed conversion factor β_m (Mkcal of feed / Mkcal of monogastric product). Share of food crops ϕ_m^{fc} and fodder ϕ_m^{fodder} in feed. Calories of food crop needed to produce one calorie of monogastric meat and eggs $\beta_m \times \phi_m^{fc}$. Feed conversion factor of extensive ruminants $\beta_{r,ext}$. Share of grass in feed $\phi_{r,ext}^{grass}$. From Bouwman et al. (2005) and modified as explained in section 2.5.4

Regions	β_m	ϕ_m^{fc}	ϕ_m^{fodder}	$\beta_m \times \phi_m^{fc}$	$\beta_{r,ext}$	$\phi_{r,ext}^{grass}$
USA	8.10	0.84	0.16	6.82	11.49	1.00
Canada	8.26	0.84	0.16	6.95	13.17	1.00
Europe	8.71	0.71	0.28	6.21	10.03	0.95
OECD Pacific	8.80	0.73	0.27	6.40	13.71	0.98
FSU	10.52	0.67	0.32	7.07	12.85	0.95
China	9.58	0.30	0.70	2.87	18.41	0.95
India	11.02	0.59	0.41	6.48	19.23	0.50
Brazil	9.85	0.70	0.30	6.88	38.23	0.95
Middle East	10.75	0.73	0.26	7.86	12.30	0.95
Africa	10.54	0.69	0.31	7.28	33.53	0.95
Rest of Asia	10.00	0.30	0.70	2.99	33.45	0.58
Rest of LAM	10.21	0.51	0.49	5.17	31.55	0.95

Table 2.5: Feed conversion factor of intensive ruminants $\beta_{r,int}$ (Mkcal of feed / Mkcal of ruminant product). Share of food crops $\phi^{fc}_{r,int}$, fodder $\phi^{fodder}_{r,int}$ and grass $\phi^{grass}_{r,int}$ in feed. Calories of food crop needed to produce one calorie of intensive ruminant meat and milk $\beta_{r,int} \times \phi^{fc}_{r,int}$. From Bouwman et al. (2005) and modified as explained in section 2.5.4

Regions	$\beta_{r,int}$	$\phi^{fc}_{r,int}$	$\phi^{fodder}_{r,int}$	$\phi^{grass}_{r,int}$	$\beta_{r,int} \times \phi^{fc}_{r,int}$
USA	11.49	0.25	0.19	0.56	2.84
Canada	13.17	0.29	0.15	0.56	3.83
Europe	10.03	0.13	0.33	0.53	1.35
OECD Pacific	13.71	0.19	0.25	0.55	2.54
FSU	12.85	0.21	0.25	0.53	2.67
China	18.41	0.10	0.28	0.57	1.85
India	19.23	0.03	0.30	0.17	0.64
Brazil	38.23	0.02	0.28	0.65	0.75
Middle East	12.30	0.29	0.34	0.30	3.56
Africa	33.53	0.08	0.28	0.59	2.70
Rest of Asia	33.45	0.09	0.25	0.35	3.04
Rest of LAM	31.55	0.06	0.24	0.64	2.01

Table 2.6: Consumed grass yield of intensive permanent pastures $\rho^{grass}_{past,int}$ in Mkcal/ha/yr. Intensive permanent pasture area $S_{past,int}$ in Mha. Production of intensive ruminant meat and milk per hectare of intensive permanent pasture $\rho^{r,int}_{past}$ ($= \beta_{r,int}\phi^{grass}_{r,int}\rho^{grass}_{past,int}$) in Mkcal/ha/yr. Consumed grass yield of extensive permanent pastures $\rho^{grass}_{past,ext}$ in Mkcal/ha/yr. Extensive permanent pasture area $S_{past,ext}$ in Mha and. Production of extensive ruminant meat and milk per hectare of extensive permanent pasture $\rho^{r,ext}_{past}$ in Mkcal/ha/yr. Yield of pastures are the quantity of grass grazed on a unit of land and not the total grass grown.

Regions	$\rho^{grass}_{past,int}$	$S_{past,int}$	$\rho^{r,int}_{past}$	$\rho^{grass}_{past,ext}$	$S_{past,ext}$	$\rho^{r,ext}_{past}$
USA	4.29	121.24	0.67	0.76	104.24	0.07
Canada	18.88	4.65	2.54	0.84	15.63	0.06
Europe	11.28	72.24	2.02	1.77	2.41	0.18
OECD Pacific	5.00	24.16	0.61	1.23	253.23	0.08
FSU	5.52	48.40	0.81	0.10	289.62	0.01
China	4.43	73.66	0.43	1.36	196.19	0.08
India	45.80	4.46	14.67	0.29	6.38	0.03
Brazil	17.75	25.32	0.71	2.10	153.37	0.06
Middle East	4.58	7.13	1.23	0.13	78.21	0.01
Africa	5.54	64.31	0.27	0.50	696.25	0.02
Rest of Asia	20.17	11.71	1.92	1.61	115.92	0.09
Rest of LAM	10.61	43.49	0.52	1.08	272.99	0.04

Table 2.7: Compartmentalisation of food biomasses in Agribiom.

Group	Compartments	SUA products lines (FAO Commodity Balances)
Plant products (terrestrial)	Vege	Wheat, rice & other grains of cereals; Bran; Maize & rice bran oils; Beans, peas & other pulses; Cassava, potatoes & other roots or tubers; Tomatoes, onions & other vegetables; Apple, oranges & other fruit; Soya bean, cottonseeds, olives & other oilseeds or tree nuts with their by-products (oils, cakes); Sugars & molasses; Wine, beer & other; Cocoa, coffee & tea; Pepper, cloves & other spices.
Animal products (terrestrial)	Rumi (grazing)	Bovine meat, mutton, goat meat & other meat; Edible offal; Meat meal; Milk (excluding butter), butter, ghee, cream; Raw animal fat.
	Mono	Eggs, pig meat, poultry meat.
Aquatic products	Aqua	Freshwater fish
	Mari	Demersal fish, pelagic fish & other marine fish with their by products (oils , meals); Crustaceans, cephalopods & other molluscs, aquatic meat & plants.

Table 2.8: Calibrated calorie price p_{cal} value in 2001 ($/Mkcal), calibrated initial slope of the production function α_{IC} in $/Mkcal and GTAP 2001 intermediate consumption IC_{χ} in billions of dollars

Regions	p_{cal}	α_{IC}	IC_{χ}
USA	13.45	1.66	6.46
Canada	17.30	3.60	1.32
Europe	15.79	3.33	8.00
OECD Pacific	27.96	12.44	2.28
FSU	17.64	7.37	4.73
China	15.76	2.53	7.10
India	7.56	2.27	2.41
Brazil	15.70	2.87	1.77
Middle East	31.61	20.30	1.49
Africa	5.93	3.79	1.43
Rest of Asia	12.38	2.44	3.13
Rest of LAM	13.14	4.12	2.67

Table 2.9: Main notations. Except p^{w}_{cal}, they are all regional. (t) means evolving through the simulation. j is the subscript of land classes.

Forcing (t)	D^{fc}_{h}, D^{m}_{h}, D^{r}_{h}	Demand of food crops (fc), monogastrics (m) and ruminants (r) products for humans (h) in kcal/yr.
	$D^{fc}_{agrofuel}$	Demand of food crops for agrofuel production in kcal/yr.
	S_{surf}	Supply of agricultural area excluding other croplands, including dynamic croplands, extensive, intensive and residual pastures in ha.
	p_{χ}	Index of fertiliser and pesticide price.
Data for calibration	ρ^{actual}_{j}	Actual yield per land class (mean through the 1999-2003 period) in kcal/ha/yr.
	IC_{χ}	Consumption of the part of the agricultural sector modelled in LPJmL from the chemical and mineral sectors in 2001 in \$ (see section 2.5.2).
Calibrated parameters	ω^{fc}_{swo}, ω^{m}_{swof}, ω^{r}_{swof}	Share of Seed, Waste at the farm level, Other uses of food crops excluding agrofuel production and Feed (only for monogastrics and ruminants) in total production of Food Crop, Monogastric and Ruminant products.
	$Q^{fc}_{other\ crop}$	Other production of food crops which is not dynamically modelled (i.e. difference between the total production from Agribiom and LPJmL production in 2001).
	α_{IC}	Initial slope of the intermediate consumption function in \$/kcal.
	FC_{tot}	Globally calibrated fixed cost of the intensive and the extensive system and aggregated with the fixed cost on croplands in \$/ha, used to compare the opportunity cost of the intensive and extensive systems.
	$\rho^{grass}_{past,int}$, $\rho^{grass}_{past,ext}$	Grazed grass per hectare of intensive and extensive pastures in kcal/ha/yr.
	$\rho^{r,int}_{past}$, $\rho^{r,ext}_{past}$	Production of ruminant product per hectare of intensive and extensive pastures in kcal/ha/yr ($\rho^{r,int/ext}_{past} = \frac{\rho^{grass}_{past,int/ext}}{\beta_{r,int/ext}\phi^{grass}_{r,int/ext}}$).
	Imp^{m}, Exp^{m}	2001 imports and exports of monogastric products in kcal/yr.

Table 2.9: Continued.

Biophysical parameters	ρ_j^{max}, ρ_j^{min}	Potential yield and minimum (no inputs) yield ($\rho_j^{min} = 0.1 \times \rho_j^{max}$) in kcal/ha/yr.
	β_m, $\beta_{r,int}$, $\beta_{r,ext}$	Feed conversion factor for monogastrics, intensive and extensive ruminants in 'kcal of feed'/'kcal of animal product'.
	ϕ_m^{fc}, ϕ_m^{fodder}, $\phi_{r,int}^{fc}$, $\phi_{r,int}^{fodder}$, $\phi_{r,int}^{grass}$, $\phi_{r,ext}^{grass}$	Share of feed categories in animal rations (fc: food crops, $fodder$: residues and fodder, $grass$: pasture grass, $monog$: monogastrics, r, int: intensive ruminants, r, ext: extensive ruminants).
Variables depending on land classes (t)	ρ_j	Yield of the land class j minimizing farmer's production cost in kcal/ha/yr.
	IC_j	Intermediate consumption of chemical and mineral inputs of the land class j in \$/yr.
	f_j^{crop}, f_j^{Pint}, f_j^{Pres}, f_j^{Pext}	Area of dynamic cropland (i.e. where crops modelled in the LPJmL model are grown), intensive pastures, residual pastures, extensive pastures of the land class j expressed as a fraction of D_{surf}.
Variables (t)	p_{cal}	Food crop calorie price in \$/kcal.
	λ	Land rent in \$/ha/yr.
	p_r	Price of ruminant calories in \$/kcal ($= p_{cal}(1 + \omega_{swo}^{fc})\beta_{r,int}\phi_{r,int}^{fc}$).
	p_{cal}^w	World calorie price in \$/kcal.
	j_{limit}	Limit land class.
	D_{surf}	Demand of agricultural area excluding other croplands, including dynamic croplands, extensive, intensive and residual pastures in ha.
	$Q_{r,int}$, $Q_{r,ext}$, Q_r	Intensive, extensive and total ruminant production in kcal/yr.
	D_m^{fc}, $D_{r,int}^{fc}$	Demand of food crops for monogastrics and intensive ruminant production in kcal/yr.
	D^{fc}	Total demand of food crops in kcal/yr.
	Imp^{fc}, Exp^{fc}	Imports and exports of food crops in kcal/yr.
	Imp^r, Exp^r	Imports and exports of ruminant products in kcal/yr.

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Chapter 3

The impact of globalisation on food and agriculture: lessons from the Nexus Land-Use

3.1 Introduction

In the coming decades actors in the agriculture sector, especially policymakers, will have to solve the complex equation of meeting growing food and energy needs, driven by the demographic evolution and the depletion of fossil fuel sources, with potentially higher input prices and smaller environmental footprint. This equation could be even more complex due to the changing socio-economic and environmental context. Thanks to rapid innovation in transport, communications technologies and liberalisation of markets, the recent period has been characterised by increasing cross-border flows of goods, services, money, people, information, and culture which have contributed to globalisation.

Globalisation is an abstract concept used to describe a complex systemic phenomenon. According to Guillén (2001), globalisation is a "fragmented, incomplete, discontinuous, contingent, and in many ways contradictory and puzzling process". In this study, we will follow the definition provided by Lambin and Meyfroidt (2009), which associates globalisation to "the worldwide interconnectedness of places and people through markets, information and capital flows, human migrations, and social and political institutions."

Globalisation may affect agriculture mainly through three channels: the intensification of international trade, the diffusion of technology and the diffusion of norms and lifestyles with resulting shifts in diets. Until now, numerical assessments of the effects of each of these channels on agriculture were rarely performed. To fill this gap, this chapter uses the Nexus Land-Use model to explore mechanims linked to globalisation that may become important influences on the future development and sustainability of the global food and agriculture system. This study focuses specifically on shifts toward convergence involving high share of meat calories in diets, which may crucially influence the demand for biomass addressed to agriculture and thus impact food prices and agricultural intensification. In addition, the sensitivity of the results to assumptions regarding international trade and technology diffusion will be tested.

The following section provides an overview of the challenges awaiting the food and agricultural system in the XXIst century and reviews the literature on agriculture and globalisation. Section 3.3 details the methodology used and presents the scenarios of diet convergence on which this study is based. Results are presented in section 3.4. Finally, a sensitivity analysis of the results to assumptions regarding deforestation, agrofuel production, potential crop yield, pasture yield and international trade is provided in section 3.5.

3.2 Context and state of the art

3.2.1 The triple challenge of agriculture

During the second half of the XXth century, motorisation, chemicalisation and progress in agronomy and plant genetics were at the origin of a strong increase in global agricultural production. According to the Agribiom database, that generates synthetic and coherent historical estimates of biomass use and resource (Dorin, 2011), the caloric yield of the global production of plant food increase by 165% between 1961 and 2007. Over the same period, the production of plant food and animal calories globally grew by 185.6% and by 165.6% respectively, while population grew only by 116%. Those changes have led to a significant improvement in the caloric ration per habitant (+25.3% of plant food calories and +37.3% of animal calories). The rise of agricultural production also contributed a shift in the framework for analysing the causes of famine and malnutrition. Breaking with the traditional model, which explains the food crisis by focusing on supply-related issues, Sen (1981) developed an alternative analysis – called “the entitlement approach” – according to which famines occur not from lack of food but from the incapacity of people to buy food for economic or political reasons (e.g., unequal distribution of wealth, dictatorship, and wars).

However, Sen – as he himself acknowledged – does not have a long-term vision of food policy. If we extend the analysis to the coming decades, tensions in the provision of food could reappear because of the conjunction of three different constraints on the agricultural production system.

The first constraint relates to the depletion of fossil fuel and the subsequent rise of fossil energy prices. This rise could have two types of consequences:

(i) First, an increase in fossil energy prices may have an important impact on food prices and on the choice of agricultural practices because energy is a major input of agriculture e.g., for operating machinery, irrigation, drying of crops, and heating infrastructures. Large amounts of energy are also used in the form of fertilisers (nitrogen, phosphorus and potassium) and other chemical inputs (e.g., pesticides). In addition to impacting food prices, growing energy prices could also encourage farmers to save fertilisers, whose price is tightly linked to those of energy, by extensifying their production. Therefore, an increase in fossil energy prices could slow increases in yields and contribute to the clearing of new lands where it is possible;

(ii) Second, higher fossil energy prices may spur the production of alternative fuels, such as agrofuel. Anticipating future tensions on energy markets, regulating authorities (such as the European Commission and Environmental Protection Agency of the United States or US-EPA) have already adopted a series of measures promoting the use of biomass energy. The International Energy Agency (IEA) provides projections of agrofuel production to 2030, which incorporate the effects of governmental measures that were enacted or adopted up to mid-2008 (IEA, 2008). These projections have been extrapolated to 2050 by Fischer et al. (2009). According to these data, the final consumption of agrofuel will grow by 180% over the period 2015-2050. More ambitious scenarios foresee a faster development of agrofuel production up to a 360% growth of final consumption over the same period.

The second constraint relates to climate change and other environmental concerns such as biodiversity loss, soil erosion, and water pollution. These concerns represent a particularly strong constraint, as agriculture is one of the few sectors to be at the forefront of both impacts and mitigation of anthropogeniic environmental change. Increases in the frequency of droughts and floods are projected to affect local crop production negatively, especially in subsistence sectors at low latitudes

(IPCC, 2007a). Using two crop models and a large array of time series on agronomic and climate data, Brisson et al. (2010) conclude that climate change is also one of the possible causes of the yield stagnation observed in Europe since the beginning of the 90s. Agriculture will have little room for managing these impacts. Indeed, due to its important contribution to global anthropogenic GHG emissions (IPCC, 2007b) (see Box 1), agriculture will at the same time have to strive to adopt less GHG-emitting practices. Doing so will entail striking an accurate balance between reducing the consumption of agricultural inputs and abandoning arable land to increase organic carbon storage. According to Vuuren et al. (2007), a significant amount of agricultural abandoned land – used in the form of "carbon plantations" – is required to stabilise GHG to 2100 concentrations at low level: 260 Mha in the 450 ppm CO_2eq scenario and 220 Mha in the 550 ppm CO_2 eq scenario, representing, respectively, approximately 18% and 15% of the global cropland area.

Box 1: Greenhouse gas emissions from agriculture (source: IPCC (2007b))

Agriculture releases significant amounts of greenhouse gases in the form of CO_2, CH_4, and N_2O into the atmosphere. CO_2 is released largely from microbial decay and the burning of plant litter and soil organic matter. CH_4 is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions. N_2O is generated by the microbial transformation of nitrogen in soils and manures and is often enhanced where available nitrogen (N) exceeds plant requirements, especially under wet conditions.

With an estimated global emission of non-CO_2 GHGs from agriculture of between 5 120 MtCO_2-eq/yr and 6 116 MtCO_2-eq/yr in 2005, agriculture accounts for 10-12% of total global anthropogenic emissions of GHGs. N_2O emissions from soils and CH_4 from enteric fermentation constitute the largest sources, 38% and 32%, respectively, of total non-CO_2 emissions from agriculture in 2005. There is however a wide range of uncertainty in the estimates of both the agricultural contribution and the anthropogenic total. Biomass burning (12%), rice production (11%), and manure management (7%) account for the remainder. CO_2 emissions from agricultural soils are not normally estimated separately but are included in the land use, land use change and forestry sector (e.g., in national GHG inventories). Consequently, there are few comparable estimates of emissions of this gas in agriculture. US-EPA estimated a net CO2 emission of 40 MtCO2-eq from agricultural soils in 2000, less than 1% of global anthropogenic CO2 emissions.

The third constraint concerns the rapidly increasing population and the resulting growth of food needs. According to the median population scenario of the United Nations (United Nations, Department of Economic and Social affairs, Population Division, 2004), the world population will experience rapid growth during the first part of the XXIst century, reaching almost nine billion by 2050. The demographic growth will be mostly driven by developing countries, including China, Brazil and India. Assuming dietary changes, these demographic evolutions will induce a 45.8% increase in the demand for food between 2001 and 2050. Considering these figures, dietary changes under the influence of globalisation, with a possible convergence towards Western lifestyles and a heavier consumption of animal calories, could dramatically accentuate this increase, leading to dramatic consequences for agriculture and land-use.

3.2.2 Agriculture and globalisation: insights from the literature

In addition to the previously mentioned constraints, the food and agricultural sector may also be impacted by the effects of the globalisation process. A sign of this process is the share of exports in food consumption, which has risen from 21.6% to 50.8% for plant food calories and from 10.5% to 17.5% for animal calories between 1961 and 2006 (Dorin, 2011) (figure 3.1).

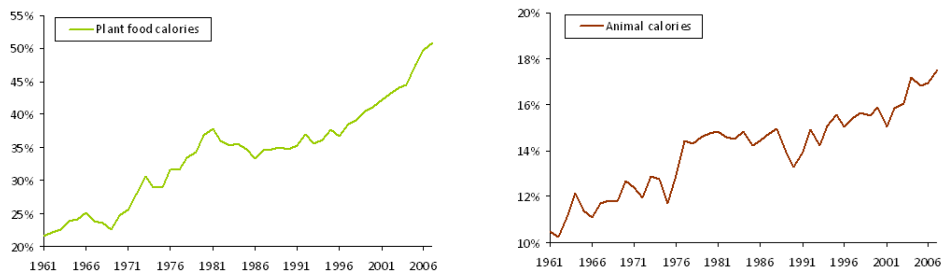

Figure 3.1: Share of plant food and animal exports in consumption (source : Dorin (2011))

The globalisation issue is a rather new research area for land-use science. Lambin and Meyfroidt (2009) identify four drivers of land conversion that are amplified by economic globalisation: (i) the displacement (or leakage) effect, which results, for example, from land zoning policies, (ii) the rebound effect, which refers to the response of consumer food demand to an increase in crop yields, (iii) the cascade effect, which causes indirect land-use change, and finally (iv) the remittance effect, which depicts how rural activities are affected by the transfer of funds from migrants to family members remaining in their country of origin. Verburg et al. (2009) study the impact of agricultural trade liberalisation on land-use and greenhouse gas emission using the coupled LEITAP-IMAGE modelling system. Their results indicate that liberalisation triggers a shift in production from North America and Europe to Latin America leading to an overall expansion of agricultural area and a global increase in total GHG emissions by about 6% compared to the reference scenario value in 2015.

The issue of diet shifts has been extensively studied in the literature (e.g., Popp et al. (2010); Bruinsma and FAO (2003)). However, this question has rarely been linked to the issue of globalisation and to the possible convergence of lifestyles. For example, Bruinsma and FAO (2003) do not consider the case of a future change in dietary preferences under the influence of globalisation: for this reason, they conjecture that India is not likely to emerge as a major meat-consuming country. The link between globalisation and convergence in diets and its consequence for agriculture are addressed in two main studies. The Millennium Ecosystem Assessment explores possible future scenarios according to two axes inspired by the Special Report on Emissions Scenarios (IPCC, 2000): the integration level – globalised or regionalised – and the approach of environmental issues – reactive or proactive. The study concludes that under all scenarios, "the projected changes in drivers result in significant growth in consumption of ecosystem services, continued loss of biodiversity, and further degradation of some ecosystem services". Nonetheless, in most scenarios, especially in globalised ones, the negative consequences of growing pressures on ecosystems may be mitigated by changes in policies, institutions, and practices. However, this rather optimistic conclusion about the effect of globalisation on ecosystems rests in part on specific assumptions about demographic changes: although economic growth is highest in the globalised scenarios, the population is between 8.5% and 18% lower than in the regionalised scenarios.

In the foresight exercise Agrimonde (Paillard et al., 2011), the impact of the diet shifts on agriculture is studied through two contrasting scenarios projecting the world's food and agricultural systems into 2050: Agrimonde GO, a business-as-usual scenario assuming some convergence of diet habits, and Agrimonde 1, a rupture scenario exploring a world that has been able to implement sustainable food production and consumption (see section 3.3.2 for further details). This study relies on a quantitative database and on experts knowledge rather than on the explicit modelling of agriculture and land-use. From there, Paillard et al. infers that the convergence of diets towards the Western model would have serious consequences for the preservation of ecosystems. They also conclude that trade regulations are essential for economic, social and environmental reasons.

By contrast, there are several studies in the social science field on the convergence of lifestyles. The intensification of exchanges between countries, spurring the diffusion of technologies, material values and a "culture-ideology of consumerism" (Sklair, 2002), is predicted to cause the standardisation of tastes and desires and the spreading of Western lifestyles (Stephan et al., 2011). Mass media, the Internet, travel and tourism, and international migration contribute to the creation of a "global village" (McLuhan, 1964) where people are increasingly exposed to a global culture and begin to adopt a common set of behaviours. However, the converging effect of globalisation has however been highly contested among social scientists. In a review of the key debates surrounding the question of globalisation, Guillén (2001) cites the views of several political and social theorists, rejecting the concept of "global culture" and underlining the possible "resurgent affirmation of identities".

A retrospective analysis of diet trends in different regions of the world between 1961 and 2007 also provides a more complex picture than simple convergence towards Western lifestyles (figure 3.2). Convergence in the consumption of plant food calories, presenting a 30% reduction in the standard deviation, can be observed. The conclusion is less clear for the consumption of animal calories. In this case, a clustering around two sets of regions can be observed. Western countries (USA, Europe and Canada) are converging towards a meat consumption of approximately 1200 kcal/cap/day. Diets in the rest of the world are characterised by growth in animal consumption but at different speeds: meat consumption is progressing rapidly in China whereas it is relatively steady in Latin American countries.

3.3 Data and methods

3.3.1 Assessing the sustainability of agriculture with the Nexus Land-Use model

To provide quantitative insights on the issue of diet convergence, we use the Nexus Land-Use model, which simulates the evolution of the agricultural system until 2050 under various assumptions regarding biomass demand. The Nexus Land-Use model belongs to the generation of global models that capture multi-scale phenomena and potential interactions among demands for food, biomass energy and forest preservation. It simulates the dynamic allocation of agricultural land-use over the globe as

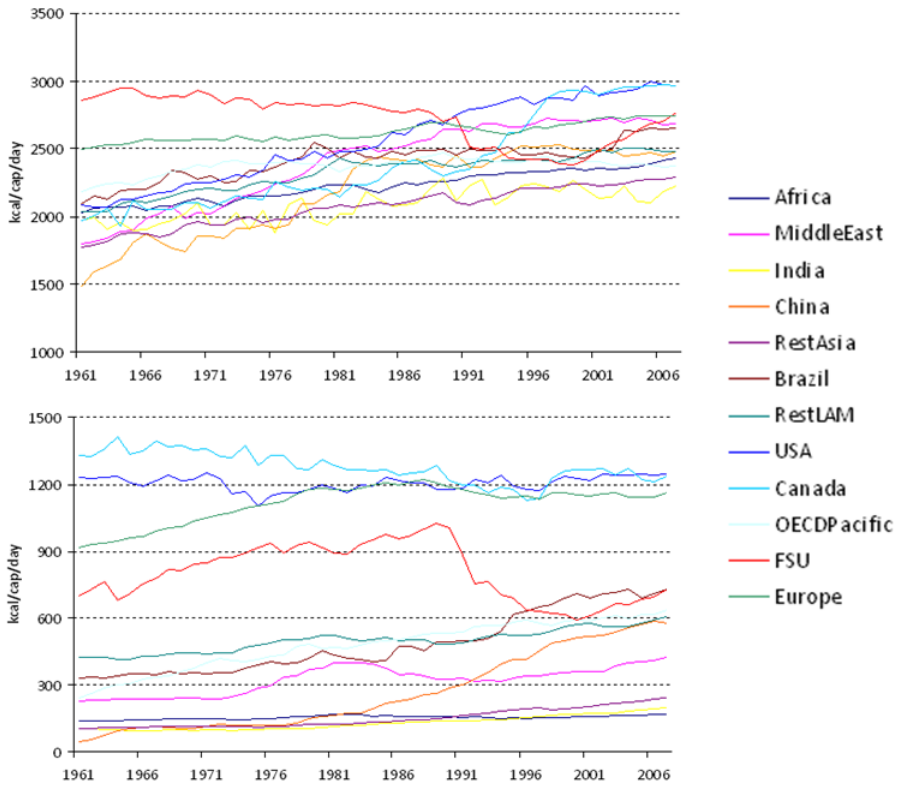

Figure 3.2: Evolutions of the consumption of plant food (up) and animal (low) calories around the world (source : Dorin (2011))

a function of biophysical as well as economic parameters (see Chapter 2).

The sustainability of the food and agricultural sector in both social and environmental terms is approximated by 3 variables: (i) the world calorie price which is the mean of regional prices weighted by the share of each region in total export. Regional prices are not set on food markets but are equal to the production costs on the marginal land, following Ricardian theory. The world calorie price reflects the social sustainability of the food and agricultural system: a price that is too high increases the risk of food crisis. Conversely, a price that is too low may impoverish farmers and plunge them into a condition of starvation; (ii) the consumption of chemical inputs (fertilisers and pesticides) that are used to increase yields. Such consumption is responsible for various environmental problems: emissions of nitrous oxide, which is a powerful greenhouse gas, eutrophication, and water pollution; and (iii) the areas of pastures dedicated to extensive grazing. The latter must be distinguished from intensive pastures, which are associated with crops to complete the feed ration in intensive animal farming systems (Bouwman et al., 2005). In the model, extensive pastures are located on the least productive or accessible lands and are used to produce ruminant calories with relatively low yields. For this reason, they can be considered as a reserve of lands that can be used more intensively. However, using the reserves of extensive pastures may have adverse effects on biodiversity and reduce the amount of carbon stored in the vegetation.

In addition to these three indicators, the value of the yield gap, defined as the average gap on cropland area between the actual and the potential yield, is also shown to provide insights into how effectively the productivity potential of soils is exploited.

3.3.2 Scenario design

This study is based on the statement that globalisation opens new possible futures beyond the simple continuation of past trends. The increased interconnectedness of the world may actually contribute to the spreading of the Western lifestyles, entailing larger share of animal products in diets. However, with for example, the increase of the number of interest and pressure groups with ecological and social mandates or the better diffusion of information on the anthropogenic environmental changes, globalisation can also contribute to the spreading of more eco-friendly and abstemious lifestyles. Between these two borders, a wide gradient of futures is possible, making more or less room for particularistic identities.

From there, possible futures in terms of diets are explored through three different illustrative scenarios (see figure 3.3). All scenarios are expressed in terms of food availability. This availability reflects the quantity of calories available to consumers, at both home and outside the home. This quantity of calories includes calories that are lost between the purchase and ingestion of the products and should not be confused with the quantity of calories actually ingested, which is difficult to estimate.

The first two scenarios are taken from the foresight exercise Agrimonde (Paillard et al., 2011). The scenario "Agrimonde GO" is the translation of the Millennium Ecosystem Assessment scenario "Global Orchestration" (Millennium Ecosystem Assessment, 2005) which depicts a "globally-driven economic development [...] with a reactive approach to ecosystems." In this scenario, globalisation rules unchallenged and spreads throughout all sectors of the economy. It is associated with high economic growth and a level of international trade that is no longer impeded by national borders. Environmental problems are second-order concerns and are taken into account only when they become acute. From there, the scenario Agrimonde GO assumes an increase of 84% of the global calorie consumption over the period 2001-2050 with emphasis on the consumption of animal calories (+191%). Agrimonde GO is considered by the authors of Agrimonde to be “business as usual”. The scenario hypothesises convergence amongst regions to a certain extent, but some regional specificities remain in 2050.

In contrast, the scenario “Agrimonde 1” corresponds to a world where the mitigation of environmental damages has the highest priority. All regions of the world are assumed to farm based on agroecological principles and to combine agricultural development and ecosystem preservation. As a consequence, this scenario assumes a convergence towards sustainable feeding conditions, through reductions in malnutrition and the excesses in nutritional intakes, a substitution of animal calories to plant food calories, and the improved management of waste throughout the consumption process. The global consumption of calories increases by 50% whereas meat consumption increases by only 36%.

In addition to these two scenarios, a third scenario, called “US Convergence”, is tested to study the hypothesis of a convergence of all regions towards US diets in 2001. This scenario is highly hypothetical, as it would suppose a major change in food habits as well as the eradication of undernutrition in the next 40 years. The realisation of these changes would be an unprecedented event in the world’s food history. However, it does illustrate the upper bound of the range of the possible outcomes of diets convergence, corresponding to a world where economic development is the only concern of people, with the lower bound being the scenario Agrimonde 1.

In this study, Agrimonde GO is denoted as AGO, Agrimonde 1 as AG1, and the scenario “US Convergence” as “USConv”.

For a relevant comparison, these three scenarios are studied with the same hypothesis on demography, energy price, deforestation, agrofuel production and potential yield. The population grows according to the median scenario projected by the United Nations (United Nations, Department of Economic and Social affairs, Population Division, 2004). The evolution of chemical input prices (fertilisers and pesticides) is computed as the mean of the projections of oil and gas prices, computed by the Imaclim-R model (Sassi et al., 2010) assuming no climate policy, and weighted by their energetic content as provided by Giampietro (2001). Increases in the calculated price of chemical inputs in different regions of the world range from 130% to 200% over the period 2001-2050. The deforestation rate is exogenously set according to the observed trends over the period 2001-2010 (FAO, 2010), as-

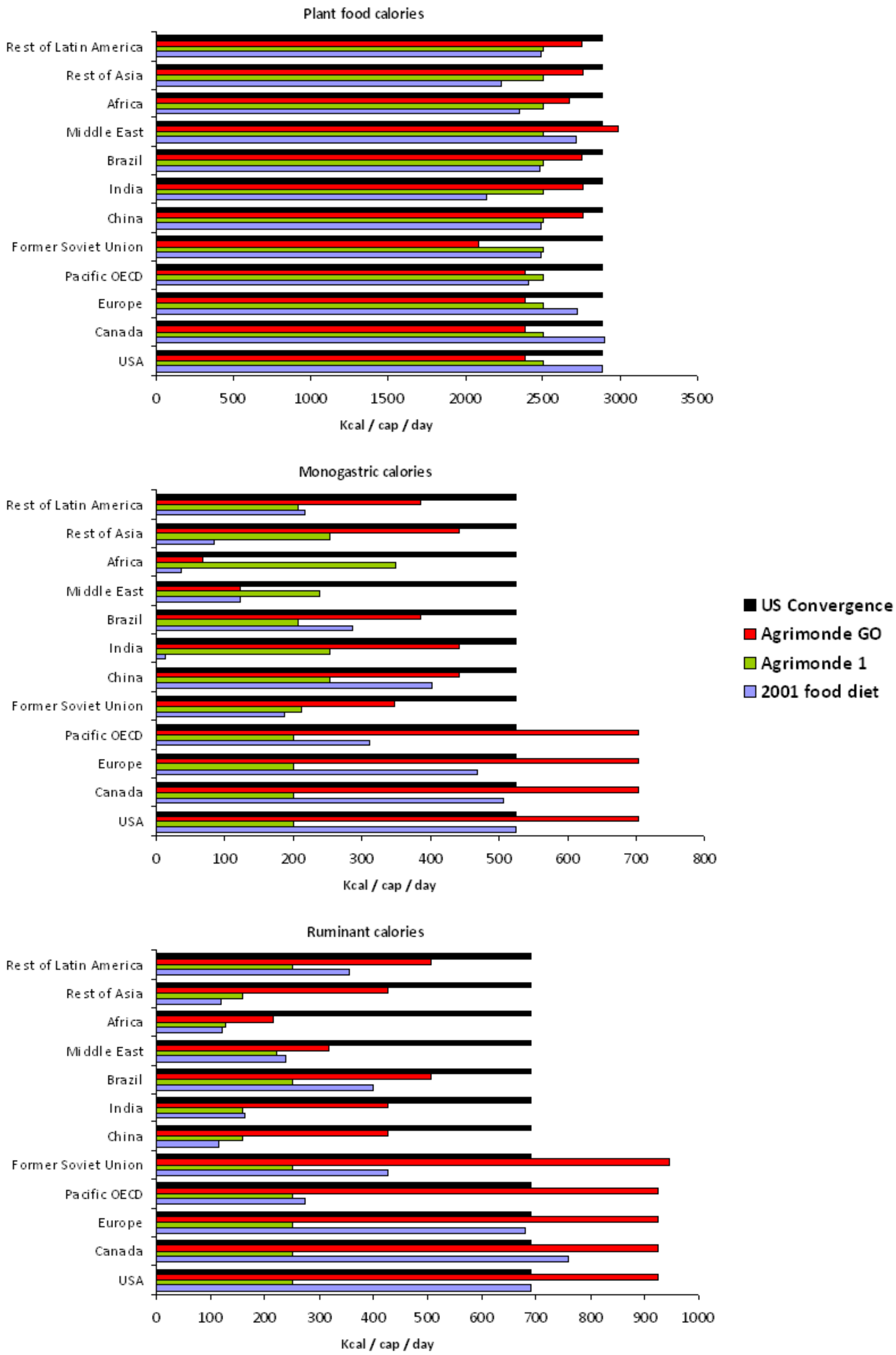

Figure 3.3: Food availability of plant food, monogastric and ruminants calories in kcal/day/cap in 2001 and in the 3 scenarios studied

suming that reforestation that occurs in some regions (such as in the US or China) ceases after 2020. The evolution of arable surfaces is directly deduced from reforestation/deforestation rates, neglecting phenomena such as the expansion of urban areas. Because it is difficult to sketch plausible agrofuel scenarios due to the issue of indirect land-use changes (Searchinger et al., 2008), which have brought great uncertainties in the development of agrofuel, and because we mainly focus on food demand, agrofuel production is set constant at its 2001 level. Finally, potential crop yields, which are used to parameterise the computation of actual yield, are set to be constant over the simulation period, implicitly assuming no land degradation and no genetic or agronomic progress.

The sensitivity of the results to assumptions on forest evolution, agrofuels production, the price-elasticity of international trade, the potential crop yields and the grass yield of intensive pastures is tested in section 3.5.

3.4 Results

3.4.1 The picture of food and agriculture in 2050 under the 3 scenarios

The design of the input scenarios results in a large range of possible futures in terms of shifts in diets. From these scenarios, the outcomes of the simulations shown in figure 3.4 correspond to even more contrasted pictures of the food and agricultural system: whereas the gap between the lower and the higher scenario in terms of food consumption amounts to 39.6% (plant food + animal calories), the gaps in the resulting world food price and the consumption of inputs between the lower and the upper bounds of the results are of several orders of magnitude.

The business-as-usual scenario, AGO, entails significant deterioration in the sustainability of the food and agricultural system. The world calorie price increases on average by 3% annually over the period 2001-2050. This increase is most pronounced in India, China and the rest of Asia and is lowest in Brazil, the FSU and Africa. In fact, the three former regions experience a strong increase in their food demand, especially with regard to ruminant calories, with relatively few extensive pasture areas to be converted into intensive agriculture. The stock of extensive pasture decreases substantially over the period 2001-2050 (-86.2% globally). The displacement of the production frontier on lower-quality lands explains the decrease in the crop yield at the beginning of the simulation period. In spite of this effect, the yield gap slightly decreases over the period 2001-2050 (from 47.7% to 45.3%). To sustain the crop yield in spite of the decreased land quality, the consumption of fertilisers and pesticides, expressed in dollars, rises sharply, especially in India, China and the rest of Asia where the pressure on land is the most pronounced.

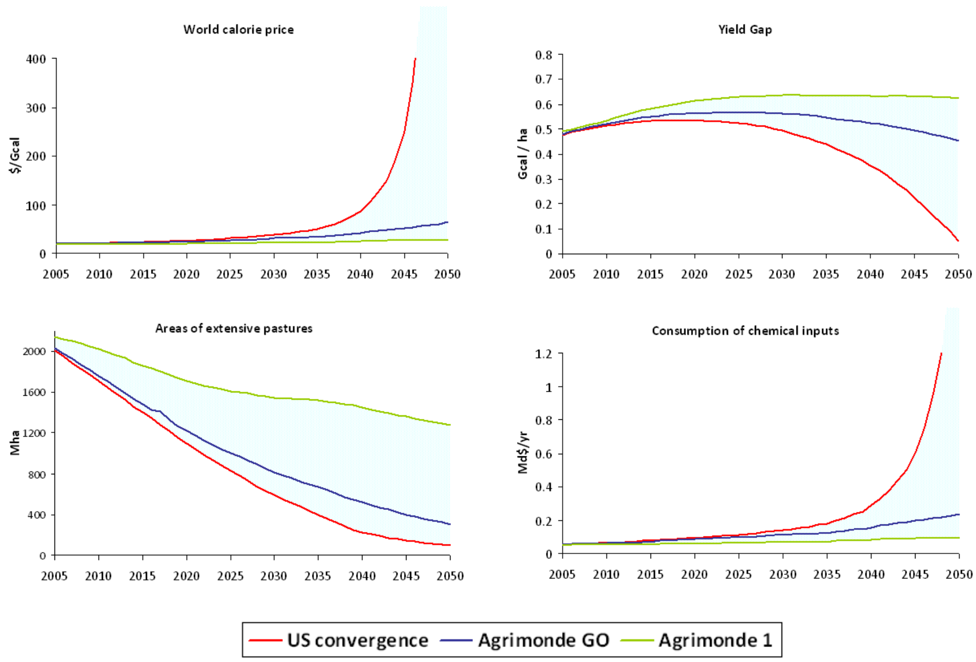

Figure 3.4: Trends in the world calorie price, the global yield, areas of extensive pastures and the consumption of chemical inputs according to a range of diets up to 2050

The convergence of diets towards sustainable consumption conditions, which characterises the scenario AG1, allows for a significant reduction of the pressure on the food and agricultural system. The increase in the world calorie price is lower than in the business-as-usual scenario AGO (+1.3% per year over the period 2001-2050). The stock of extensive pasture decreases moderately during the simulation period (-42% globally). The yield gap rises from 47.7% to 62.4%. As a consequence, the consumption of fertilisers and pesticides per year and per hectare is 26.3% smaller in 2050 than in 2001.

In sharp contrast with this latter vision, the USConv scenario corresponds to highly unsustainable conditions of production and consumption. According to the model's results, the pasture area is not sufficient to meet the demand for animal calories from 2047 on, reason why we present the results only before this date. The world calorie grows by 7.3% per year on average over the period 2001-2046.

To support the strong increase in food consumption, the agricultural production potential is nearly fully exploited. Almost all of the stock of extensive pastures is used for intensive agriculture: only 7% of the initial stock of extensive pastures at the base year 2001 remains in 2046. As in the previous scenarios, the displacement of the production frontier on lower-quality lands explains the decrease in the crop yield at the beginning of the simulation period. Over the period 2001-2046, the world crop yield grows by 0.18% per year on average. This corresponds to a reduction in the yield gap from 47.7% to 19%. To enable such a yield increase, the consumption of fertilisers and pesticides per unit of land is 6.4 times higher in 2046 than in 2001.

3.4.2 Identifying amplifying mechanisms

The results tend to confirm the intuition of Lambin et al. (2001) that globalisation amplifies or attenuates the driving forces of land-use change. As far as diets are concerned, several reasons explain this effect. First, globalisation affects the consumption of animal products whose production process is heavily land-intensive. Across the different regions of the world, between 10 and 37 feed calories (including calories of plant food, fodder, grass and scavenging) are necessary to provide one ruminant calorie (Bouwman et al., 2005). Consequently, the consumption of animal products has a stronger impact than plant food consumption on agriculture and land-use.

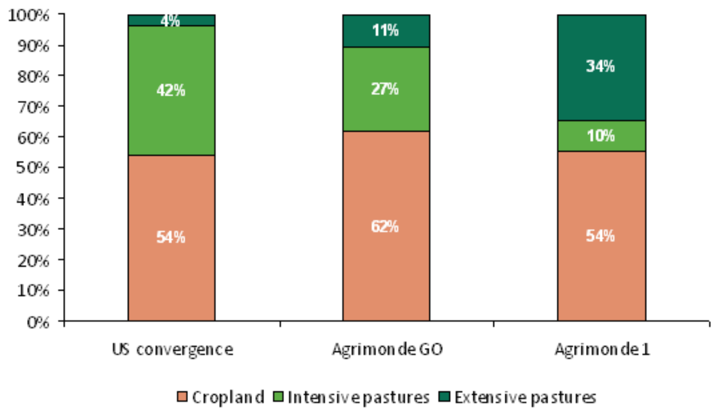

Figure 3.5: Global land-use in 2045 under the 3 globalisation scenarios

In the Nexus Land-Use model, livestock production can be intensified by replacing grass with food crops, residues and other roughages in the animal feed rations (see Chapter 2). Nonetheless, even in the case of an intensive production, animal feed in most regions of the world is mainly composed of grass. Figure 3.5 shows the world land-use in 2050 disaggregated among cropland, intensive pastures and extensive pastures, which provide grass respectively in the cases where livestock production is intensified or not. In the AG1 scenario, the agricultural system is weakly constrained by food demand and there is room for extensive agriculture. As a result, there are large areas of pastures, which are primarily extensive. In the AGO scenario, the increase in land pressure stimulates the intensification of livestock production. Grass is replaced by food crops and other roughages, leading to a sharp reduction in extensive pastures and to an increase in cropland and intensive pastures. In the USConv scenario, the pressure on land is such that there are almost no more extensive pastures. The high demand for animal products requires corresponding areas of intensive pastures. Because it is assumed in the Nexus Land-Use model that, contrary to crop yield, pasture yield cannot be intensified, pasture areas act as global constraints on land-use pushing up crop yields and the associated consumption of fertilisers and pesticides as well as increasing land rents and food prices. The assumption of a constant pasture yield thus crucially influences the results. In the sensitivity analysis, the consequences of relaxing this assumption are explored.

Non-linear effects represent another amplifying mechanism. In the Nexus Land-Use model, such effects are driven by two biophysical features of the agricultural ecosystem. First, lands are of heterogeneous quality. According to Ricardian theory, higher-quality lands are put into cultivation first. This effect is represented in the Nexus Land-Use by modelling a production frontier that separates an extensive and an intensive livestock production system, with the former system located on the least productive lands and the latter located on the most productive lands. As the pressure on land rises, this frontier moves toward lower-quality lands and the average land productivity progressively decreases.

The second non-linear effect relates to the form of the function that determines the actual crop yield. In the Nexus Land-Use, the actual crop yield is driven by the consumption of pesticides and fertilisers. Farmers are assumed to trade off between the use of chemical inputs and the expansion of agriculture on new lands. When the price of land is high (in case of high demand with low land availability) in comparison with the price of fertilisers and pesticides, farmers chose to increase the crop yield per hectare. In the model, the crop yield function has the form of a yield response function to fertiliser application that are simulated by crop models (Brisson et al., 2003; Godard et al., 2008) generalised to all types of fertilisers (nitrogen, phosphorus, potassium) and to pesticides. It is thus a non-linear function that asymptotes towards a potential yield. In other words, increasing the yield further requires significant chemical inputs as the actual yield approaches its biophysical asymptote, significantly amplifying variables such as production costs and food prices.

3.5 Sensitivity analysis

For the sake of simplicity, in this sensitivity analysis, we focus on the value of the world calorie price. This variable can actually be considered a good indicator of the tensions on land-use and of the resulting issues for the sustainability of the food and agricultural system. In the Nexus Land-Use modelling framework, an increase in calorie price is associated with agricultural intensification, i.e., a reduction of the yield gap, through the use of larger amount of chemical inputs and a diminution of the areas of extensive pasture. Because the pasture area is not sufficient from 2047 onward to meet the demand for animal calories in the USConv scenario (see section 3.4.1), thus obscuring the model's results beyond this date, we consider the values of the world calorie price in 2045. The sensitivity of the results is assessed through 2 types of indicators:

- the difference in 2045 world calorie price between the scenarios AG1, AGO and USConv;
- the average annual evolution of the world calorie price up to 2045.

3.5.1 Agrofuel

The development of agrofuel is motivated by various types of arguments. In recent years, it has been mainly justified by environmental concerns and the mitigation of climate change. However, several studies have contested the capacity of agrofuel to reduce GHG emissions in comparison with a fossil fuel reference (Searchinger et al., 2008; Melillo et al., 2009). Following these conclusions, modifications to the regulation of the bioenergy sector are under way in Europe and in the US, casting doubts on the future of the agrofuel industry. This is why the agrofuel production has been set constant to its 2001 level in the reference scenarios.

However, other factors, such as energy security or fossil fuel depletion, could renew interest in agrofuel. For this reason, we investigate two variants of first-generation agrofuel development adapted from IEA (2008). In the first variant, named "median", agrofuel production reaches 150 Mtoe (2 Ecal) in 2050, representing respectively 14.7%, 10.5% and 7.9% of the total calorie production in the AG1, AGO and USConv scenarios. The second variant, named "high", has an optimistic expectation of agrofuel development, showing production reaching 300 Mtoe (4 Ecal) in 2050, representing respectively 29.3%, 21% and 15.8% of the calorie production in the AG1, in AGO and in USConv scenarios. In both variants, the US and Brazil are the two main producers.

Table 3.1: Sensitivity of the results to assumptions regarding agrofuel production

		Default	Median	High
Difference in the	*AG1 / AGO*	96.6%	124.5%	156.1%
2045 world calorie price	*AG1 / USConv*	1 159.6%	2 464.8%	10 783.2%
Average annual	*AG1*	1.30%	1.56%	1.78%
change in the	*AGO*	3.02%	3.40%	3.93%
world calorie price	*USConv*	7.26%	9.15%	12.96%

Although relatively marginal in both variants, the additional production of agrofuel leads to a doubling of the gap in the 2050 world calorie price between the AG1 and USConv scenarios in the median variant (1 159.6% compared to 2 464.8%), whereas this gap is multiplied by around 9 in the high variant (1 159.6% compared to 10 783.2%). Additionally, according to our results, agrofuel development accelerates the increase in the calorie price in all scenarios. This effect is all the more important than the initial production is high: the increase in the world calorie price amounts to 0.26 points in AG1 compared to 1.89 points in the USConv scenario when using the median variant (and 0.49 points compared 5.7 points when using the high variant).

3.5.2 Forest evolution

The causes of deforestation are both numerous and complex. Among them, an increase in agricultural price is generally considered to be a strong incentive promoting the clearing of new lands. Sharp price changes in the AGO and USConv scenarios may thus trigger deforestation rates beyond those observed in recent decades. For this reason, we explore a variant in which every regions engages in deforestation up to 2050, unlike what has been effectively observed over the period 2000-2010 in some countries (e.g., the US, Europe, and China) (FAO, 2010). In this variant, called "increased deforestation", agricultural surfaces increase by 22.2% over the simulation period compared with 11% in the reference case. Contrasting with this vision, a second variant can be considered where environmental concerns prevail, leading to a halt in deforestation. In this variant, called "no deforestation", agricultural areas are held constant over the simulation period.

Table 3.2: Sensitivity of the results to assumptions regarding deforestation

		Default	No deforestation	Increased deforestation
Difference in the	*AG1 / AGO*	96.6%	180.2%	66.6%
2045 world calorie price	*AG1 / USConv*	1 159.6%	13 922.5%	329.4%
Average annual	*AG1*	1.30%	1.53%	1.18%
change in the	*AGO*	3.02%	3.88%	2.33%
world calorie price	*USConv*	7.26%	23.92%	4.51%

The values displayed in table 3.2 show that the gap in the 2050 world calorie price between the different scenarios studied is very sensitive to assumptions of deforestation: the gap is reduced by two thirds in the “increased deforestation” variant and multiplied by 12 in the “no deforestation” variant.

The results also reveal that policies aimed at reducing deforestation could have major impacts on the food and agricultural system. First, halting deforestation leads to an accelerated rise in calorie prices in comparison with the reference case: +0.23 points in the AG1 scenario, +0.88 points in the AGO scenario and up to +16.6 points in the USConv scenario. Such a policy also entails the intensification of the agricultural production: in the AGO scenario, the average per hectare consumption of fertilisers and pesticides increases by 41% in comparison with the reference case, and the area of extensive pastures decreases by 37%. For this reason, policies aimed at reducing deforestation must be carefully designed so that the environmental gains in terms of preserved forest areas are not counteracted by an increase in calorie prices or by the growing intensification of agriculture with its associated ecological impacts.

3.5.3 International Trade

As with shifts in diets, globalisation is viewed as being associated with the intensification of international exchange and the progressive withdrawal of national barriers to free trade. To explore the consequences of a relaxation of trade barriers, we run the Nexus Land-Use for different values of the price elasticity of exports. This parameter accounts for the different sources of imperfect competition on international markets, such as import barriers or export tariffs. The higher is this parameter, the more exports are driven by relative prices.

In the model, trade in crops (including feed for animals) and trade in ruminant products are represented separately. Following Hertel and Tsigas (1988), the price elasticity of exports – denoted as ϵ in table 3.3 – is set at 4 for crop products and at 1 for ruminant products. For this sensitivity analysis, two variants are studied. The first of this variant sets the elasticity of crops and ruminants to be equal at 4, and the second multiplies the initial values of both elasticities by 2.

Table 3.3: Sensitivity of the results to assumptions regarding international trade

		Default	$\epsilon_{veg} = 4$ $\epsilon_{rumi} = 4$	$\epsilon_{veg} = 8$ $\epsilon_{rumi} = 4$
Difference in the 2045 world calorie price	*AG1 / AGO*	96.6%	103.9%	83.8%
	AG1 / USConv	1 159.6%	1113.9%	1 071.0%
Average annual change in the world calorie price	*AG1*	1.30%	1.39%	1.37%
	AGO	3.02%	3.01%	2.75%
	USConv	7.26%	7.18%	7.07%

The results shown in table 3.3 suggest that removing barriers to free trade slightly reduces the gap in the 2045 world calorie price between AG1 and the USConv scenarios. Increasing the price elasticity of trade has a slight impacts on the calorie price over time in the AG1 scenario but strongly attenuates the increase in the calorie price in the AGO and the USConv scenarios. Indeed, when international trade reacts more strongly to relative prices, the production is allocated to the regions that are best suited for agriculture (i.e., those with the largest reserves of agricultural productivity). International trade thus contributes to the mitigation of the global pressures on land that induce increases in the world calorie price.

However, at a smaller scale, freer trade has some detrimental effects. According to Ramankutty et al. (2008), the countries with the largest reserves of cultivable croplands are located mainly in tropical South America and Africa. Additionally, large amounts of farmlands have been abandoned since the collapse of the Communist bloc (Vuichard et al., 2009). Accordingly, as the price elasticity increases, exports grow in Africa, the Former Soviet Union and Brazil, but decrease in other regions[1] (see table 3.4).

Using the productivity reserve of tropical regions is hazardous, as it may trigger either an expansion of the agricultural surfaces over pristine forests or an intensification in the production with the subsequent conversion of pastures into croplands and an increase in the consumption of fertilisers and pesticides. In tropical regions, pastures as well as forests are valuable in terms of both their biodiversity and their sequestration of organic carbon. For example, the Brazilian cerrado is a 200Mha savannah that can be used for raising cattle and whose biodiversity is estimated at 160 000 species of plants, fungi and animals (Dias et al., 1992). According to our results (see table 3.4), Africa, the Former Soviet Union and Brazil experience a reduction in their areas of extensive pastures[2] with an increase (or a relative stagnation in the case of Brazil) in the consumption of chemical inputs.

The analysis reveals that the overall gain in terms of sustainability brought by a freer trade could be offset by large local losses in terms of either biodiversity or terrestrial carbon sink.

3.5.4 Potential crop yield

Globalisation may also be associated with a greater diffusion of technical progress. This could, for example, concern genetic progress and plant breeding. In the Nexus Land-Use model, such progress will induce an increase in the potential crop yield. We thus analyse two variants. The first variant assumes a 50% increase in potential crop yields until 2050, and the second variant assumes a 100% increase over the same period. The first variant corresponds to a 0.8% yearly average growth. By

[1] Exports also rise in Middle East, but this region represents a smaller share of international trade.

[2] Areas of extensive pastures also fall in Europe, but in this region, the area of extensive pastures is not significant.

Table 3.4: Variation in the 2050 value of exports, consumption of chemical inputs and extensive pasture areas when the default price elasticity of exports is multiplied by 2

Regions	Exports	Consumption of chemical inputs	Extensive pasture areas
USA	-18.7%	-12.1%	54.1%
Canada	-13.2%	-13.8%	-
Europe	-6.4%	-62.3%	-87.1%
Jap./Aus./NZ	-1.1%	-3.5%	14.1%
FSU	**3.6%**	**0.9%**	**-11.5%**
China	-77.0%	-6.4%	5.9%
India	-86.0%	-5.4%	7.6%
Brazil	**-0.7%**	**-0.8%**	**-37.0%**
Middle East	17.7%	-0.8%	0.2%
Africa	**29.1%**	**11.5%**	**-12.5%**
Rest of Asia	-46.7%	-9.3%	11.1%
Rest of Lat. Am.	-1.8%	-5.2%	13.8%

comparison, Evenson and Gollin (2003) estimates that an increase in the crop yield due to modern varieties – which should be a good proxy for our increase in the potential yield – amounted to 0.857% per year on average in the developing countries over the period 1981-2000.

The projections of the potential crop yield simulated in the two variants generate large reductions in the gaps in the 2045 world calorie price between the 3 scenarios studied (table 3.5). In both cases, the increase in the calorie price diminishes greatly: given a 50% increase in the potential crop yield, the annual increase in the calorie price in the USConv scenario is close to the calorie price increase simulated for the business-as-usual scenario AGO in the reference case.

3.5.5 Pasture yield

The results analysis carried out in section 3.4.2 revealed that pasture areas are a crucial determinant of the pressure on land-use in the most meat-based diets. In the reference case, pasture yield is assumed to be constant over the simulation period. This assumption may overestimate the pasture areas required to satisfy animal food demand. In some regions, the potential to increase pasture yield actually exists, as,

Table 3.5: Sensitivity of the results to assumptions regarding potential crop yield

		Default	+50%	+100%
Difference in the	*AG1 / AGO*	96.6%	58.6%	49.5%
2045 world calorie price	*AG1 / USConv*	1 159.6%	202.9%	123.4%
Average annual	*AG1*	1.30%	0.79%	0.39%
change in the	*AGO*	3.02%	1.83%	1.29%
world calorie price	*USConv*	7.26%	3.30%	2.20%

for example, in Brazil where the livestock density per hectare of pasture is relatively low. For this reason, we test the sensitivity of the results to different assumptions regarding the evolution of the yield for intensive pastures[3]. Two variants are explored. In the first variant, the pasture yield is multiplied by 2 up to 2050, and in the second variant, the pasture yield is multiplied by 4 over the same period. The growth rates of the pasture yield chosen for the two variants are mainly illustrative and do not consider the actual potential to increase pasture yield, the assessment of which is beyond the scope of this study.

Table 3.6: Sensitivity of the results to assumptions regarding pasture yield

		Default	x2	x4
Difference in the	AG1 / AGO	96.6%	46.8%	32.8%
2045 world calorie price	AG1 / USConv	1 159.6%	166.9%	95.7%
Average annual	AG1	1.30%	1.29%	1.23%
change in the	AGO	3.02%	2.16%	1.87%
world calorie price	USConv	7.26%	3.52%	2.76%

[3]Yield on intensive pasture is defined as the production of intensive ruminant meat and milk per hectare of intensive permanent pasture (see Chapter 2)

According to the results shown in table 3.6, increasing the pasture's productivity appears to be an effective option to reduce the pressure on the food and agricultural system in the scenarios with the highest share of meat consumption – AGO and USConv. The gap in the 2045 world calorie price between the three scenarios studied is strongly reduced due to the smaller increase of the calorie price in the scenarios AGO and USConv. Because the consumption of meat is lower in AG1, variations in the pasture yield have a lower impact in this case.

3.6 Conclusion

Due to the complexity of globalisation, assessing its impact on food and agriculture in the first half of the XXIst century is a challenging task. Among the numerous and complex mechanisms by which globalisation could impact the food and agricultural system, this chapter concentrates on the issue of lifestyle convergence and on the resulting shifts in diets.

The first conclusion that emerges from this study is that globalisation expands the range of plausible futures, making it possible various types of diet scenarios to 2050, from a convergence toward healthy diets in a world where ecological concerns predominate to a convergence towards US lifestyles and a higher proportion of animal products. Integrating this set of scenarios into the Nexus Land-Use model provides extremely contrasting visions of the 2050 food and agricultural system: whereas the convergence towards the US diet entails large impacts and cannot be sustained by the agricultural system to 2050 with current trends of expansion of arable land due to a lack of pasture areas, the healthy diet scenario allows for a significant reduction of the impacts on the food and agricultural system in comparison with the business-as-usual diet scenario. On the whole, the different visions of the 2050 agriculture system appears to depict an even larger range than the input scenarios.

The Nexus Land-Use modelling framework makes it possible to identify the mechanisms that amplify the gap between the different scenarios under study. Among these mechanisms, the consumption of animal products is central. Because livestock production is particularly land-intensive, meat and milk consumption have a stronger impact on agriculture than plant food consumption. In particular, pastures providing grass to feed animals act as a constraint on land-use, leading to an increase in crop yields and food prices. Finally, in the scenarios with some convergence towards Western lifestyles, the production system progressively catches up with its biophysical asymptotes in terms of the availability of productive lands and potential crop yield, triggering non-linear effects that further amplify the increase in calorie price, the consumption of fertilisers and pesticides and the expansion of intensive agriculture areas.

The sensitivity analysis of the results to assumptions regarding agrofuel production, deforestation, international trade, potential crop yields and pasture yields provides numerous insights. First, the consequences of agrofuel development and policies of reducing deforestation on agriculture have larger detrimental side effects on food and agriculture when the proportion of animal calories in diets is large. Therefore, reorienting dietary habits toward plant food calories appears to be necessary to mitigate the potential negative effects of agrofuel and forest preservation policies.

Reducing trade distortions contributes to a slight easing of the global pressure on land but produces some detrimental local effects, such as concentrating the production in tropical regions with rich biodiversity and carbon content. In addition, by disconnecting consumption and production places and by increasing the interdependency among regions, international trade raises the possibility of leakage or indirect effects. Consequently, assessing the environmental impact of biomass products becomes increasingly complex. This has spurred intense controversy over agrofuel, but all categories of goods produced from biomass that do not meet basic needs (meat, coffee, tea, alcohols...) should be concerned as well.

Finally, increasing potential crop yields markedly reduces pressure on the food and agricultural system. Interestingly, an increase in pasture yields allows for a substantial diminution of the impacts of all scenarios – especially the scenario assuming the most meat-intensive diet – on agriculture. Given the doubts that exist on the potential to increase crop yields (e.g., Searchinger (2009)), this increase in pastures productivity thus appears to be a promising avenue to reduce land-use tensions.

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Chapter 4

Climate change mitigation and global warming impacts on agriculture: guidelines for coupling the Nexus Land-Use to Imaclim-R and ORCHIDEE

4.1 Introduction

The previous chapter explored the possible futures of the agricultural system in the changing socio-economical context of globalisation. Due to rising concentration of atmospheric greenhouse gases, it is increasingly probable that the climatic environment will change as well. This will have a direct impact on land-use and agriculture as crop yields are highly dependent on climatic conditions. This could also have indirect consequences on the agricultural sector by spurring climate change mitigation policies based on biomass energies.

To explore this issue, we present in this chapter the guidelines for 2 types of model couplings. In the first one, we use the Nexus Land-Use to explicitly represent the land constraint into the IMACLIM-R model (Sassi et al., 2010). At the core of this coupling is the question of the land rent: how does it evolve when biomass is used to stabilize emissions, and what is its influence on agricultural price and gross domestic product (GDP)? The second example concerns the coupling between the Nexus Land-Use and the vegetation model ORCHIDEE (Krinner, 2005). The objective is here to represent the consequences for the agricultural system of the crop yield variations computed by ORCHIDEE under a climate change scenario.

This chapter is more about giving future prospects of the Nexus Land-Use than presenting robust results, as all the features of the different types of coupling are not integrated yet. However, they can help to give insights on the issues related to the cost of mitigation policies under various assumptions of biomass development and to the impact of climate change on the agricultural system.

In the following section, we present the IMACLIM-R model and its components that relate to biomass. In section 4.3, the basic coupling methodology between IMACLIM-R and the Nexus Land-Use is detailed. Section 4.4 is devoted to the representation of the climatic feedback and the coupling with ORCHIDEE.

4.2 Projecting the economy throughout the XXIst century: the IMACLIM-R model

4.2.1 The basic features of the IMACLIM-R model

The IMACLIM-R model aims at investigating climate, energy and development inter-related issues. The model was built in an attempt to address three methodological challenges: (i) to incorporate knowledge from economics and engineering sciences, (ii) to support the dialogue with and between stakeholders, (iii) to produce scenarios with a strong consistency, especially concerning the interplay between development patterns, technology and growth (Sassi et al., 2010). These goals led to the development of a recursive structure articulating a static general equilibrium framework, which includes sector-specific dynamic modules now concerning energy, transportation and industry.

IMACLIM-R is based on an explicit description of the economy both in money metric values and in physical quantities linked by a price vector. This dual vision of the economy, which comes back to the Arrow-Debreu theoretical framework, is a precondition to guarantee that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent sets of relative prices. The existence of explicit physical variables allows for a rigorous incorporation of sector-based information about how final demand and technical systems are transformed by economic incentives, especially for very large departures from the reference scenario. This information encompasses : (i) engineering-based analysis about economies of scale, learning by doing mechanisms and saturation in efficiency progress; (ii) expert views about the impact of incentive systems, market or institutional imperfections and the bounded rationality of economic behaviours.

Because it is almost impossible to find functions with mathematical properties suited to cover large departures from a reference equilibrium over one century and flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade, 1993), IMACLIM-R uses an innovative method where the production function is replaced by a recursive structure that allows for a systematic exchange of information between :

(i) An annual static equilibrium module, in which the production function mimics the Leontief specification, with fixed equipment stocks and fixed intensity of labour, energy and other intermediary inputs, but with flexible utilisation rate. Solving this equilibrium at time step t provides a snapshot of the economy at this date, a set of information about relative prices, levels of output, physical flows and profitability rates for each sector and allocation of investments among sectors;

(ii) Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models, which take into account the economic values of the previous static equilibrium, assess the reaction of technical systems and send back this information to the static module in the form of new input-output coefficients for calculating the equilibrium at $t + 1$. Each year, technical choices are flexible but they modify only at the margin the input-output coefficients and labour productivity embodied in the existing equipments that result from past technical choices.

The static equilibrium is Walrasian in nature: domestic and international markets for all goods — not including factors such as capital and labour — are cleared by a unique set of relative prices that depend on the behaviours of representative agents on the demand and supply sides. Consumers final demand results from solving the utility maximisation program of a representative consumer. The distinctive features of this program consist in the maximisation of a utility function under the constraint of both an income and a time constraints (see Sassi et al. (2010) for more details).

The utility function U is a Linear Expenditure System (LES) form incorporating basic needs (see 4.3.3). Its arguments are the goods $C_{k,i}$ produced by the agriculture, industry and services sectors, with basic needs $bn_{k,i}$, and the services of mobility $S_{k,mobility}$ (in passenger-km pkm) and housing $S_{k,housing}$ (in square metres). Households thus make a trade-off between the consumption of different goods and services, including the purchase of new end-use equipment stocks.

$$U = \prod_{goods\ i} (C_i - bn_i)^{\xi_i} \cdot (S_{housing} - bnhousing)^{\xi_{housing}} \cdot (S_{mobility} - bn_{mobility})^{\xi_{housing}}$$

Producers are assumed to operate under shortrun constraints of (i) a fixed maximal production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with the equipment built and accumulated previously, and (ii) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of a good i in region k requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods j and $l_{k,i}$ of labour. In this context, the only margin of freedom of producers is to adjust the utilisation rate $\frac{Q_{k,i}}{Cap_{k,i}}$ according to the relative market prices of inputs and output, taking into account increasing costs when the production capacities utilization rate approaches one.

4.2.2 Biomass modelling in Imaclim-R

Bioenergy can be used in two types of applications: (i) liquefaction to produce fuels for transport or (ii) gasification in conjunction with or without carbon capture and storage (CCS) to generate electricity.

Two categories of agrofuels are represented in IMACLIM-R, ethanol and biodiesel. They are both directly usable in internal combustion vehicles and are supposed to be perfectly substitutable with gasoline and diesel.

As things stand, this module consists simply in supply curves of ethanol and biodiesel. These curves are calibrated on the results of sectoral modelling (IEA, 2006). They have been interpolated to integrate an annual continuum of the curves between 2001 and 2100 into the IMACLIM-R model. Production potentials increase with time simultaneously with cost reductions thanks to constant technical progress. These production potential increases are mainly due to maturing, at middle term, of so-called second-generation technologies: the cellulosic-lignite branch for ethanol and the biomass liquefaction branch for biodiesel. The penetration of agrofuels on the liquid fuels market depends on their competitiveness and availability. Both aspects are calculated by equalling out the marginal production costs of each type of agrofuel and the price of fossil fuel, with an eventual increase due to a carbon tax in the case of climate policies. Global production is ventilated in the regions of the model according to specific distribution keys.

As for agrofuel, the biomass electricity sector is modelled using supply curves. Following the modelling specifications of IMAGE described in Hoogwijk et al. (2009), land resources available for biomass production dedicated to power generation are restricted to abandoned agricultural land and rest land. To be consistent with this vision, the biomass supply curves in the case of electricity production are derived from those designed by Hoogwijk et al. (2009) for the four SRES scenarios (IPCC, 2000). Table 4.1 presents the biomass potential in 2050 in each of the scenarios studied. A conservative assumption of 302 EJ/year corresponding to the A2 scenario has been retained. Supply curves for each of the twelve regions of Imaclim and for the whole world are shown in figure 4.1.

Table 4.1: Geographical biomass potential for energy in EJ/year in 2050. Source: Hoogwijk et al. (2009)

Regions	A1	A2	B1	B2
USA	53	33	36	49
Canada	18	12	14	13
Europe	23	22	17	25
Jap./Aus./NZ	55	34	35	30
FSU	127	68	88	78
China	107	23	77	46
India	27	14	14	6
Brazil	87	24	63	43
Middle East	13	8	4	3
Africa	139	53	81	15
Rest of Asia	10	7	3	4
Rest of LAM	17	4	11	5
World	676	302	443	317

It is assumed that short-rotation woody crops, such as willow and poplar, are grown on abandoned agricultural land and rest land and are used to produce electricity. After being processed, biomass is fed to Integrated Gasification Combined Cycle power plants (BIGCC plants) to produce electricity. The technology considered excludes combined heat and power production.

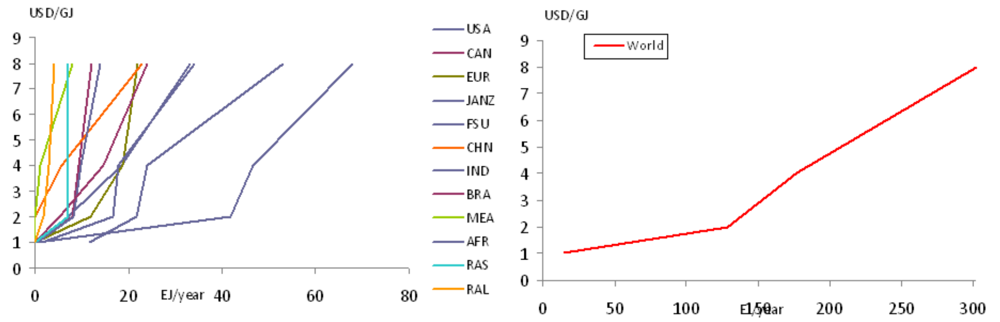

Figure 4.1: Supply curves for biomass electricity in the twelve regions of Imaclim (left graph) and in the whole world (right graph). Source: Hoogwijk et al. (2009)

4.2.3 The role of biomass and the rent issue

The Imaclim-R modelling framework is used to provide insights on the socio-economic consequences of emissions scenarios that are considered for the fifth assessment report of the international panel on climate changes (IPCC). In this respect, projections of the world economy have been carried out under the constraint of a reduction of GHG emissions to 450 ppm and 550 ppm levels. Two sets of variants have been considered: a first one in which the potential of biomass for electricity is set at its default level of 302 EJ/yr, and a second one in which it is limited to 110 EJ/year. In Imaclim-R, the use of biomass for electricity is supposed to be carbon-neutral, as all the GHG emitted during the production and consumption cycles are supposed to be offset by the storage of organic carbon during the growth of the biomass. This assumption is crucial for the results but has been highly criticised by many authors (Searchinger et al., 2008; Johnson, 2009).

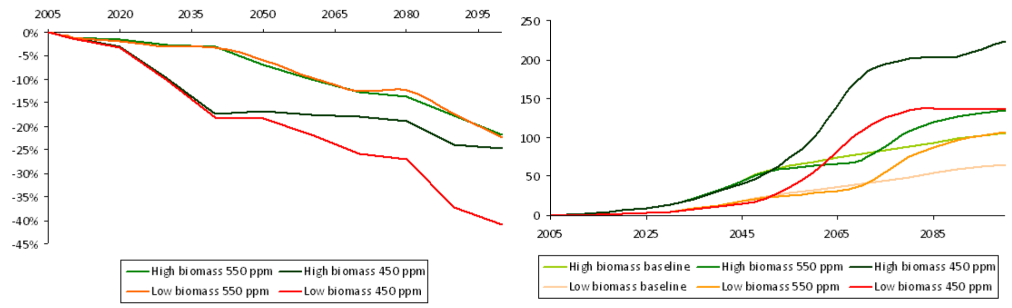

Figure 4.2: GDP losses (left graph) and production of primary biomass energy in exajoule (right graph) under different emissions scenarios

The results show that compared to a baseline scenario with no mitigation policy, the losses of the considered scenarios in terms of gross domestic product (GDP) in 2100 range within 21% and 41% (see figure 4.2). The use of energy from biomass appears to be an effective option to reduce those losses: at the 550 ppm level, the gap is slight (−21.8% compared to −22.4% without biomass), but at the 450 ppm level, the use of biomass energy absorbs a sizable share of the losses (−24.8% compared to −40.8%). Figure 4.2 provide the production of primary biomass energy (used for electricity and as liquid fuel) that is associated with each variant. In the default assumption of biomass availability, the production of energy from biomass in the 550 ppm and 450 ppm amounts to 135 EJ and 224 EJ respectively in 2100 compared to 107 EJ and 136 EJ in the low potential case.

The use of cost-supply curves of biomass energy from Hoogwijk et al. (2009) and IEA (2006) guarantees that such a production is possible from a biophysical point of view, considering the availability and productivity of land under different development scenarios to 2050. The feedback between the whole economy and the agricultural sector is however not complete because the value of the land rental costs in Imaclim-R, that is incorporated in the mark-up, evolves without regard to the actual land availability. As this is a component of agricultural prices, the feedback of an increasing use of biomass energy on the agricultural markets is thus not represented in a realistic way. As a consequence, the potential losses from increased food prices in terms of consumer surplus are not fully accounted for.

To illustrate the potential influence of the land rental costs, we compute its value in each of the 6 scenarios (baseline, 550 ppm, 450 ppm in either high or low biomass potential) using the Nexus Land-Use model. In this model, the rent is Ricardian in nature, hence it is the sum of a scarcity and a differential rent, the latter reflecting the heterogeneous qualities of land.

To carry out these simulations, we use the Gross Annual Increment (GAI) per hectare[1] as a proxy of the yield of woody crops. Smeets et al. (2007) report an average value of the GAI of $39 GJ/ha/yr$. For these simulations, we hypothesize that an improvement of technologies, practices and species selection will allow for a quadrupling of the woody crop yield until 2050. Without this very optimistic assumption, an increased deforestation rate would be necessary to preserve enough agricultural

[1] Smeets et al. (2007) define the GAI as “the annual forest growth, excluding mortality. Mortality is dependent on site characteristic (e.g., climate, slope, soil structure), age stand and management system. In general, in undisturbed full-grown forests mortality offsets annual growth and the net annual increment (NAI) is zero, while in managed forests mortality rate can be as low as 2-6% of the GAI. Data on GAI are measured in $m^3/ha/yr$ for wood of a minimum diameter at breast height of zero cm.”

surfaces for non-energy use, conflicting thus with the the carbon-neutrality assumption of biomass. In addition, the simulation horizon is limited to 2060. Beyond this date, the surfaces dedicated to biomass electricity represents a share of the agricultural areas that is so high (more than 50% in several regions even with our very optimistic assumption on woody yield), that food and agrofuel demand cannot be met given our assumptions on the agricultural production system.

We assume in addition that food diets follow the Agrimonde 1 scenario. Deforestation is set according to its observed trend during the 2000-2010 period, that is around 0.2% per year. Finally, the values of energy prices are taken from Imaclim-R and correspond to the various tested scenarios.

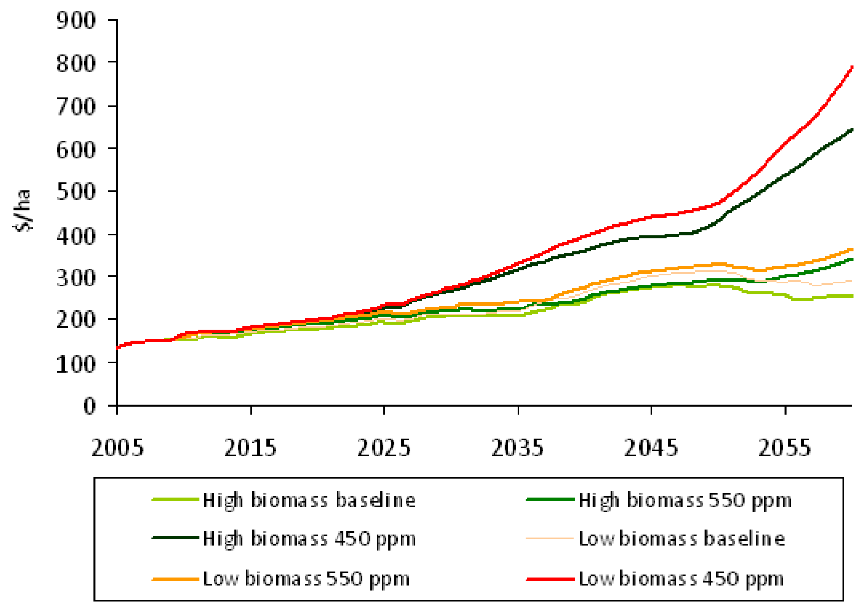

Figure 4.3: Evolution of fertilisers and pesticides prices (including carbon tax) computed by the Nexus Land-Use under different emissions scenarios and assumptions on biomass potential

The effect of bioenergy production on land rent is twofold. On the one hand, for a given deforestation scenario, the land area that has to be devoted to bioenergy production reduces the surfaces of land available for agricultural use. This increases both the scarcity and the differential rent because this spurs farmers to put into cultivation lower-quality lands. On the other hand, bioenergy production makes it possible to partly offset the depletion of fossil fuel sources and to reduce the subsequent rise of energy prices. In the Nexus Land-Use, the evolution of fertilisers and pesticides prices is computed as a weighted mean of oil, gas and electricity prices evolutions – including a carbon tax in mitigation scenarios – according to their energy content provided by Giampietro (2001). This evolution is shown on figure 4.3 for the different scenarios studied. In each case, the rise of chemical inputs price is lower in the high biomass scenario than in the corresponding low biomass scenario. As a consequence, in their trade-off decisions between expanding agricultural surfaces and using more chemical inputs, farmers are more willing to intensify the production and spare land in the high biomass scenario than in the low biomass scenario.

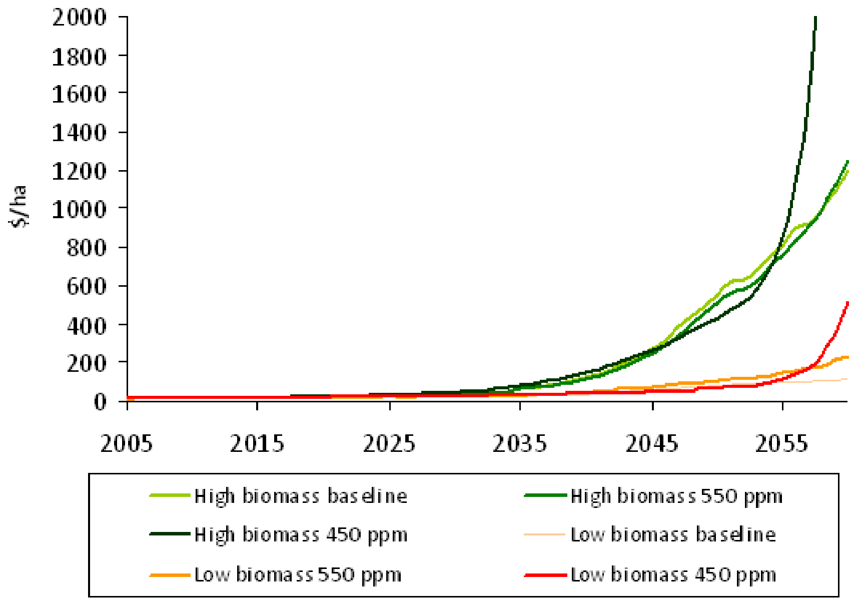

Figure 4.4: Evolution of the world land rental costs per hectare under different emissions scenarios and assumptions on biomass potential

Our results reveal a clear segmentation between scenarios with and without restrictions on the biomass potential (see figure 4.4). The value of the land rent per hectare in 2060 in the baseline and the 550 ppm scenario is between 5 and 10 higher in the high biomass potential variant than in the low biomass one, and up to 35 times higher for the 450 ppm scenario, showing a strong effect of the biomass production on the land market. From there, several questions arise: what will be the consequences on agricultural prices and how will be the land rent redistributed within the economy? To tackle this issue, it is necessary to progress in the coupling of the Nexus Land-Use to the Imaclim-R model.

4.3 Coupling the Nexus Land-Use to IMACLIM-R: methodological guidelines

This section presents the basic methodology to incorporate the land rent calculated by the Nexus Land-Use into Imaclim-R. This coupling is done in two steps. First, a reduced-form of the Nexus Land-Use is inserted in the Imaclim-R architecture in order to provide an evaluation of the cost of biomass. Then, the land rent that is associated which each level of biomass demand is fed back into the Imaclim-R agricultural price.

4.3.1 The demand for biomass energy

Within the Imaclim-R theoretical framework, the nexus are commonly designed as submodels replacing sectoral production function (see section 4.2.1). They aim at modifying the technical constraints applying to the economy in static equilibrium by modelling the relations of production at a disagreggated level and taking into account engineering-based knowledge.

In the current version of Imaclim-R, cost curves from IEA (2006) and Hoogwijk et al. (2009) are used to model the production function of the bioenergy sector (see section 4.2.2). To compute a land rent that is consistent with each level of biomass demand several options are possible. The first one would be to endogeneously represent the biomass energy sector into the Nexus Land-Use. Such a modelling work is however complex due to the lack of robust calibration data (Kretschmer et al., 2008). In addition, the relevance of a model based on economic behaviours is not granted as biomass energy production largely depends on public supports (see Chapter 1). Therefore, a second option consists in simply replacing the cost curves for primary biomass energy provided by IEA (2006) and Hoogwijk et al. (2009) by curves from the Nexus Land-Use. In this option, the production of biomass energy is not endogenously driven by prices but is exogenously set.

Figure 4.5 presents an example of the costs of primary bioenergy in 2050 calculated by the Nexus Land-Use for each of the Imaclim regions and for the world. These curves have been computed considering a zero deforestation rate, no technical progress on potential yields and the Agrimonde 1 food scenario (see Chapter 3). These curves have been calculated for biomass used as fuel only, excluding biomass used in the electricity sector.

These results can't be directly compared with those of Hoogwijk et al. (2009) for several reasons. First, the scenario used in those simulations is quite restric-

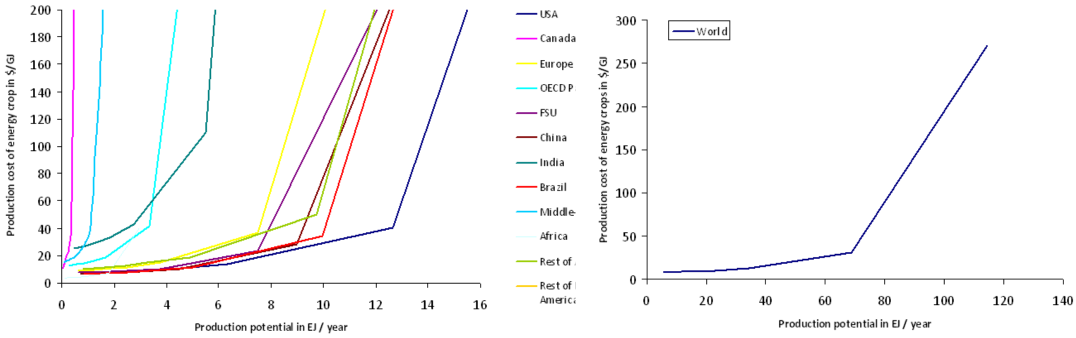

Figure 4.5: Supply curves of primary biomass energy calculated by the Nexus Land-Use in the twelve regions of Imaclim (left graph) and in the world (right graph)

tive, especially in the extent that contrary to Hoogwijk et al. (2009), there is no technological learning and only first-generation agrofuels are taken into account. Secondly, our analysis remains quite rudimentary: the agrofuel sector is modeled using parameters that are surrounded by a high range of uncertainties (see Chapter 2); sugarcane – one of the most effective plant to produce agrofuel – is not included in the representative crop modeled by the Nexus Land-Use, leading thus to a probable underestimation of agrofuel crop yields.

4.3.2 Incorporating the land rent into IMACLIM-R

The constraints faced by the agricultural sector are of various types. Among them, land constraint will be of peculiar importance due to the increasing amount of land required to satisfy the demands for food, biomass energy and carbon sequestration. For this reason, the Nexus Land-Use has been especially designed to account for the tensions on land. To this end, it calculates a Ricardian rent reflecting the scarcity and the heterogeneous qualities of land (see Chapter 2).

Land rent computation relies on a detailed representation of intensification processes, implying changes in livestock production systems and variations of fertilisers and pesticides consumption with embodied energy. As a consequence, the Nexus Land-Use also accounts for the constraint relating to the use of energy. However, as already mentioned in Chapter 2, due to our focus on land and energy, labour and capital are more roughly modelled and cannot be accurately used to update the Imaclim-R values.

In Imaclim-R, prices are derived from the equality between the value added and the remuneration of the factors of production:

$$p_{k,i}Q_{k,i} - \sum_j p_{IC_{k,j,i}} IC_{k,j,i}Q_{k,j,i} = \Omega_{k,i}w_{k,i}L_{k,i}(1 + tax^w_{k,i}) + \pi_{k,i}p_{k,i}Q_{k,j,i} + \lambda_{Imaclim}$$

With $Q_{k,i}$ the ouput of the sector i and country k, $w_{k,i}L_{k,i}(1 + tax^w_{k,i})$ the labor remuneration including taxes, $\Omega_{k,i}$ the utilisation rate ($\frac{Q_{k,i}}{Cap_{k,i}}$), $\pi_{k,i}p_{k,i}Q_{k,j,i}$ the capital remuneration (or the mark-up) and $\lambda_{Imaclim}$ the land rent computed by IMACLIM-R. Here, this latter term is disconnected from any biophysical reality and evolves without regard to the effective feedback on the land constraint.

To correct this bias, the coupling between Imaclim-R and the Nexus Land-Use consists therefore in replacing $\lambda_{Imaclim}$ by the land rent per unit of output λ_{Nexus} as computed in the Nexus Land-Use. Then, chemical and energy intermediary consumptions from Imaclim-R are updated using the values of the Nexus Land-Use ($IC_{k,ener,Nexus}$) to be consistent with the intensification level that it has been computed. As the agricultural sector in Imaclim-R is larger than in the Nexus Land-Use – because it incorporates the agroalimentary industry –, chemical and energy intermediary consumptions are shared according to distribution keys calibrated at the base year using the GTAP database (α_{agro}). Following this methodology, the agricultural price in the coupled system gives:

$$\begin{aligned} p_{k,agr} &= \textstyle\sum_{j\setminus ener} p_{IC_{k,j,agr}} IC_{k,j,agr} + p_{IC_{k,ener,agr}}(\alpha_{agro}IC_{k,ener,agr} + (1 - \alpha_{agro})IC_{k,ener,Nexus}) \\ &\quad + \Omega_{k,i}w_{k,agr}l_{k,agr}(1 + tax^w_{k,agr}) + \pi_{k,agr}p_{k,agr} + \lambda_{Nexus} \end{aligned}$$

In response to land rent variations, the agricultural market will converge to new price and quantity equilibrium (p*,Q*). For a price-elastic demand, as is the case for bioenergy, the agricultural sector will arbitrate between passing the rise of land rent on to prices but facing a decrease of demand, and maintaining prices at their initial level to preserve demand. In both cases, the land rent will be paid to the landowner mostly by the producers, through the decrease of their selling or of their profit. Obviously, farmers could be assumed to own their land, in which case a rise of land rent won't have any noticeable effect on the economy. If the demand is rigid, as is generally the case for food (see section 4.3.3), the land rent will be paid mostly by consumers through higher prices and potential food crisis in the poorer region of the world. In the various cases, tax system could be modified to redistribute the land rent among producers and consumers in a specific way.

Because of the crucial role of the food demand response to prices and incomes on the land rent redistribution, we analyse in the following section the various functional forms that are used to model the food demand system.

4.3.3 Selecting the food demand system

World economic development over the last sixty years have been followed by major shifts in food consumption patterns with a strong increase of the animal share in diets in lower income countries. This has shown the influence of income evolutions on food diet composition. In the coming decades, emerging economies are projected to keep growing with possible convergence towards Western references. At the same time, tensions on food markets may reappear due to the conjunction of demographic evolutions, increasing energy prices and environmental concerns, as it has already been the case in 2008.

To compute plausible evolutions of the demand for food, we select a functional form that reflects two important stylized facts:

(i) Engel's Law that states that an increase in the income of a household involves an increase in food consumption expenditures less than proportional than to income increase. This implies an income elasticity less than one and a negative value of the elasticity of the food budget share with respect to income (also called "Engel elasticity");

(ii) King's Law that states that the demand for food is weakly elastic to prices. This law applies nevertheless essentially to grains products, which can be viewed as necessities, while consumption of animal calories appears to be responsive to prices to a larger extent, with resulting shifts in the food composition from plant food to animal calories and conversely. For this reason, special attention should be devoted to cross-price elasticities that drive such mechanisms.

In addition, any system of demand equations should satisfy the following conditions of consumer demand theory in order to respect rationality assumption: (i) homogeneity of degree zero in income and prices[2] (no money illusion), (ii) symmetry and negative definiteness of the compensated crossprice terms (cross-substitution effect between good X and Y must be the same as the cross-substitution effect between Y and X), and (iii) share-weighted sum of income elasticities equal to 1 (so that the total expenditure is equal to the sum of individual expenditures on different commodities and goods).

Several functional forms can be used to compute the demand for food according to income and price evolutions and consumer preferences: Cobb-Douglas, CES (Con-

[2]This condition holds only for Marshalian demand. Hicksian demand functions are homogenous of degree zero in prices only

stant Elasticity of Substitution), Double-log, Translog (Transcendant Logarithm), and the AIDS (Almost Ideal Demand System). Their mathematical expressions as well as their main features are presented in tables 4.2 and 4.3.

Due to its simplicity, the Cobb-Douglas was a popular functional form to simulate demand systems. It was used for example in the old version of GTAP (Malcolm, 1998). This function is however extremely restrictive as it implies a proportional variation between consumption and income due to the unitary income elasticity, and as relative prices variations do not influence the consumption content due to the absence of cross-price elasticities. For this reason, the Cobb-Douglas function is less and less employed in partial or general equilibrium models.

The CES function has also a unitary income elasticity but allows for substitution between goods to some extent. This function is frequently used in international trade models to estimate substitution between domestic and imported goods as in the MIRAGE model (Bchir et al., 2002). The double-log is a generalized form of CES depicting the substitution possibilities between products with greater details. However it implies a constant income elasticity which is hardly realistic for growing economies where the budget shares devoted to food generally decrease. The double-log is a widely used functional form in studies of food supply and demand models, as for example the IMPACT model (Rosegrant et al., 2001).

The Linear Expenditure System (LES) function is a modified form of the Cobb-Douglas function incorporating a subsistence or committed expenditure level denoted C_i^{min}. Compared to the Cobb-Douglas or the CES (Constant Elasticity of Substitution) functions, the LES function presents several advantages: it entails an Engel elasticity, the income elasticity is not forced to one, and contrary to the Cobb-Douglas, modifications in the composition of food diets in response to relative price variations are possible. However, the form of the LES implies that as income increases without bound, the income elasticities converge monotonically to unity, thus contradicting the Engel's Law. This function is currently used in the Imaclim-R model (see section 4.2.1).

One can cite in addition two others functions that are referred to as flexible functional forms as they provide a second-order approximation to any utility function. The AIDS is derived from a particular cost function (see table 4.2) depicting a gradient between subsistence (u=0) and bliss (u=1). The Transcendental Logarithmic or translog is a closely related consumer demand system. It is usually derived by applying Roys Identity to a quadratic, logarithmic specification of an indirect utility function written in terms of expenditure-normalized prices (Holt and Goodwin, 2009).

Results from projections using the previous functional forms show that they tend globally to over-estimate food demand (Yu et al., 2003). This is mainly due to the fact that income elasticities are not bounded. As a consequence, large income variations, that characterised long-term projections, involve less and less realistic changes along the simulation.

To overcome this problem, several solutions are possible. The first one consists of using "An Implicitly Direct Additive Demand System" (AIDADS) Yu et al. (2003) actually show that such a demand system has been shown to outperform competitors in its ability to predict per capita food demand across the global income spectrum and represents a substantial improvement, particularly in the case of rapidly growing developing countries. An alternative strategy consists of using exogenous scenarios in combination with a functional form. The scenarios would define the overall consumption of calories while the functional form would specify the repartition between plant food and animal calories according to consumer preferences, and price and income evolutions. This solution also presents the advantage of providing a simple solution for translating the IMACLIM-R variables expressed in values into quantities to run the Nexus Land-Use model.

4.4 Modelling the climatic feedback

Land-use reacts to the evolutions of the economic system as well as to those of the biospheric one. In the coming decades, climate changes could actually significantly affect the conditions of agricultural production through the rise of temperatures and the variations of precipitations. The actual effect is however difficult to assess due to the complexity of the mechanisms at play.

4.4.1 Yield variations in a climate change scenario

To give some insights on this issue, Viovy et al. (2010) used the vegetation model ORCHIDEE (Krinner, 2005) to simulate the yield changes for the A1B scenario of the IPSL-CM4 climatic model. From an economic scenario depicting a future world of very rapid economic growth, rapid introduction of new and more efficient technologies and a development of energy technologies balanced across energy sources (IPCC, 2000), the IPSL-CM4 model simulates an increase in temperatures going from +2 to +4 degrees in the North of Canada, a moderate rise in precipitations in the North and at the equatorial level, and a fall in the south of Europe, in North

Table 4.2: Comparison of the most used functional forms of demand

Specification	Objective function	Demand function
Cobb-Douglas	$U(c) = \prod_i C_i^{\alpha_i}$	$C_i = \frac{\alpha_i}{p_i} R$
CES	$U(c) = \left[\sum_i \alpha_i^{1/\sigma} C_i^{1-1/\sigma}\right]^{\frac{1}{1-1\sigma}}$	$C_i = \frac{\alpha_i p_i^\sigma}{\sum_j \alpha_j p_j^{1-\sigma}} R$
LES	$U(c) = \prod_i \left(C_i - C_i^{min}\right)^{\alpha_i}$	$C_i - C_i^{min} = \frac{alpha_i}{p_i}\left(R - \sum_i p_i C_i^{min}\right)$
Double-log	$U(c) = \sum_i \alpha_i C_i^{1-1/\sigma}$	$lnC_i = \alpha_i + \sum \gamma_{ij} \ln p_j + \epsilon_i R$
Translog	$lnV(p,R) = \alpha_0 + \sum_{i=1}^{n} \eta_i ln \frac{p_i}{R} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} ln\frac{p_i}{R} ln\frac{p_j}{R}$	$\omega_i = \frac{\alpha_i + \sum_i \gamma_{ij}\ln(p_j/R)}{\sum_i \alpha_i + \sum_i \sum_j \gamma ij \ln(p_j/R)}$
AIDS	$lnC(P,u) = (1-u)\ln a(P) + u \ln b(P)$ $\ln a(P) = \alpha_0 + \sum_{i=1}^{n} \eta_i \ln p_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \eta_{ij} \ln p_i \ln p_j$ $\ln b(P) = \ln a(P) + \beta_0 \prod_{j=1}^{n} p_j$	$\omega_i = \alpha_i + \sum \gamma_{ij} \ln p_j + \epsilon_i \ln \frac{R}{P}$

Table 4.3: Elasticities and properties comparison for different functional forms

Specification	Income Elasticity $\epsilon_i = \frac{\partial C_i / C_i}{\partial R / R}$	Cross price elasticity $\eta_{ij} = \frac{\partial C_i / C_i}{\partial p_j / p_j}$	Engel elasticity $E_i = \frac{\partial \omega_i / \omega_i}{\partial R / R}$
Cobb-Douglas	unity	null	none
CES	unity	$\eta_{ij} = -(1-\sigma)\frac{\alpha_i p_j^{1-\sigma}}{\sum_j \alpha_j p_j^{(}1\sigma)}$	none
LES	$\epsilon_i = \frac{\alpha_i R}{p_i C_i^{min} + \alpha_i (R - \sum_i p_i C_i^{min})}$	$\eta_{ij} = -\alpha_i \frac{p_j C_j^{min}}{C_j^{min} + \alpha_i (R - R^{min})}$	$E_i = \frac{(1-\alpha_i)}{(1-\alpha_i) + \alpha_i \frac{R}{R^{min}}}$
Double-log	constant	constant	$E_i = \epsilon_i - 1$
Translog	$\epsilon_i = 1 + \frac{-\sum_i \gamma_{ij}/\omega_i + \sum_j \gamma_{ij}}{-1 + \sum_i \sum_j \gamma_{ij} ln(p_j/R)}$	$\eta_{ij} = -\delta_{ij} + \frac{\gamma_{ij}/\omega_i - \sum_j \gamma_{ij}}{-1 + \sum_i \sum_j \gamma_{ij} ln(p_j/R)}$	$E_i = -1 - \sum_i \gamma_{ij}/\omega_i$
AIDS	$\epsilon_i = \frac{\alpha_i}{\omega_i} + 1$	$\eta_{ij} = \gamma_{ij}\frac{R}{p_i p_j}$	$E_i = \frac{\alpha_i P}{\omega_i R}$

America and on all the tropical tape (see figure 4.6).

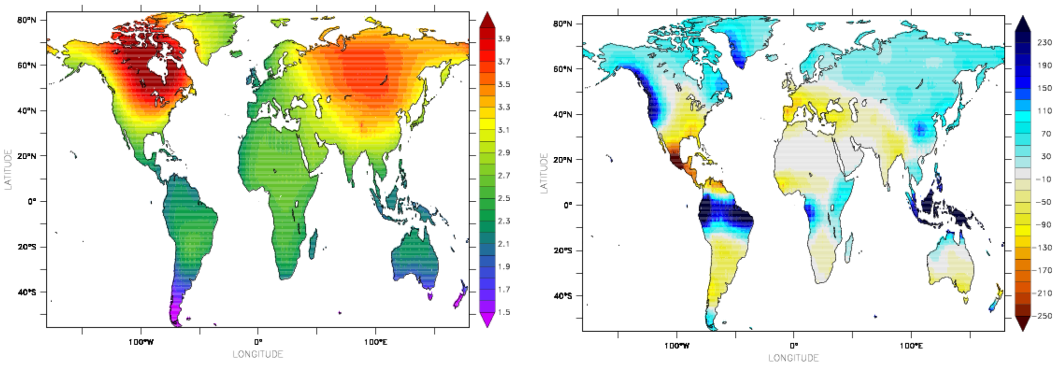

Figure 4.6: Evolution of temperatures (left graph in °C) and precipitations (right graph in mm/year) in the IPSL-CM4 A1B scenario

Three types of crops are considered in ORCHIDEE: wheat, maize and tropical crops (millet and sorgho). For each type of culture, two simulations are carried out: (i) in the first one, both the effects of CO_2 and climate are taken into account. It is furthermore assumed that the theoretical fertilisation effect of CO_2 is not limited by the availability of mineral nitrogen in the natural ecosystems; (ii) in the second one, the CO_2 is set constant to its current value (370 ppm) in order to separate the CO_2 fertilisation effect and the climate one.

Results of the simulations in the case of wheat are presented in figure 4.7. In the first simulation with the CO_2 fertilisation effect, we observe an overall increase in yields with broad regional differences: an increase in Northern and Southern zones of production and a reduction in Central Europe. In the North, the combined effect of the increase in temperatures, precipitations and CO_2 leads logically to a rise in yields. The increase of yield in the South in spite of the fall of precipitations can be explained by the fact that the annual cycle of crops begins earlier and is shortened by the rise of temperatures[3]. The cycle shifts over one earlier period of spring when the soil is in better condition in terms of water content. The hydrous stress is therefore paradoxically reduced in spite of the fall of precipitation. Simulations without the CO_2 fertilisation effect shows a fall in yields in almost all the surfaces where wheat production has been simulated. It appears thus clearly out that the CO_2 fertilisation effect is a potentially dominant factor of the yield increase.

These results must be analysed with caution for several reasons. First, the evaluation of each type of effect – and especially the CO_2 fertilisation effect – is

[3]the beginning of the cycle and its duration being dependent on the sums of temperature

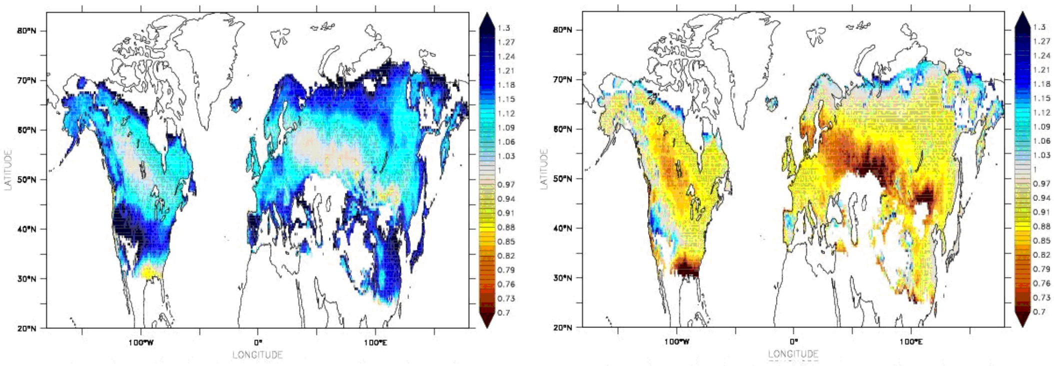

Figure 4.7: Evolution of wheat yield in % between the periods 2070-2100 and 2000-2030 with climate and CO_2 fertilisation (left graph) and climate only (right graph). Source: Viovy et al. (2010)

surrounded by large uncertainties. Secondly, the effect of climate variability, which is likely to rise with climate change, is not accounted for, hampering so a large part of the potential negative impacts of climate change.

4.4.2 The impact of climate change on crop yield, land rent and agricultural trade

The design of the Nexus Land-Use, combining biophysical and economical knowledge into a single coherent framework, makes it possible to give some insights on the impacts of climate change and rise in CO_2 concentration on the agricultural system. The use of such a model to calculate the impact of climate change on agriculture constitutes a new approach as this kind of analysis has been mainly carried out so far by econometric models (see for example Seo et al. (2009)). Compared to the econometric method, our approach will provide less precise results in terms of spatial disaggregation, but enables to represent the evolutions of market conditions, through food price and international trade. Our method also allows to better account for the trend of the world demand of biomass and the food prices, which are generally regarded as constant in econometric models.

In these prospects, we firstly compute the evolution rate of the Nexus Land-Use potential yield δ_{cc} given the estimations provided by ORCHIDEE for the 3 crops – wheat (δ_{cc}^{wheat}), maize (δ_{cc}^{maize}) and tropical crops (δ_{cc}^{trop}) – weighted by the proportion of each crop type in the total of crop ($\frac{\sum_l f_{wheat/maize/trop,l}}{\sum_{CFT} f_{CFT,l}}$), assuming that the potential yield of the other crops remains constant:

$$\delta_{cc} = \frac{\sum_l f_{wheat,l}}{\sum_{CFT} f_{CFT,l}} \delta_{cc}^{wheat} + \frac{\sum_l f_{maize,l}}{\sum_{CFT} f_{CFT,l}} \delta_{cc}^{maize} + \frac{\sum_l f_{trop,l}}{\sum_{CFT} f_{CFT,l}} \delta_{cc}^{trop}$$

The resulting potential yield evolution (see table 4.4) is then incorporated into the Nexus Land-Use production function by modifying its asymptote ρ_j^{max}:

$$\rho_j(IC_j) = \hat{\rho}_j^{max} - (\hat{\rho}_j^{max} - \rho_j^{min}) \frac{\alpha_{IC}(\hat{\rho}_j^{max} - \rho_j^{min})}{IC_j + \alpha_{IC}(\hat{\rho}_j^{max} - \rho_j^{min})}$$

With

$$\hat{\rho}_j^{max} = (1 + \delta_{cc})\rho_j^{max}$$

An actual yield is deduced from the minimisation of the production cost (see Chapter 2). This yield is the result of biophysical constraints, embodied by the potential yield and the form of the production function, and economic trade offs between the land price and the fertilisers and pesticides price.

Using this method, we run the Nexus Land-Use until 2050 with the Agrimonde GO food scenario (see Chapter 3) and a zero deforestation rate. Fertilisers and pesticides prices are driven by Imaclim-R energy prices in the baseline scenario with a low biomass potential. Agrofuel production is set constant to its 2001 level. On figure 4.8, the resulting actual yield and land rent (including differential and scarcity rents) are compared to a reference case where no climate and CO_2 effects are simulated. In most regions, climate change and the CO_2 fertilisation effect lead to an increase in the actual crop yield in comparison to the reference case. As expected, Canada experiences the highest rise (+15.91% in 2050). Actual yield strongly decreases in Africa (-8.03% in 2050) and to a lesser extent in Brazil and in the rest of Latin American (-3.65% and -2.08% in 2050).

Climate change and the CO_2 fertilisation effect lead to a reduction of the land rent in all the regions of the world in comparison to the reference scenario. In terms of surplus, this fall means a loss for producers and a gain for consumers. For most regions, this is a mechanical consequence of the yield increase which depresses food prices. On the other hand, this is a quite surprising result given the fall of the actual yield in Africa, Brazil and Rest of Latin America. This can be nevertheless explained when looking at the variations of the trade balance between the reference case and the climate and CO_2 effect case (see figure 4.9). In these three regions, the fall of yields is responsible of a rise of their relative prices on the international food markets which deteriorates in its turn the trade balance. Consequently, the production is

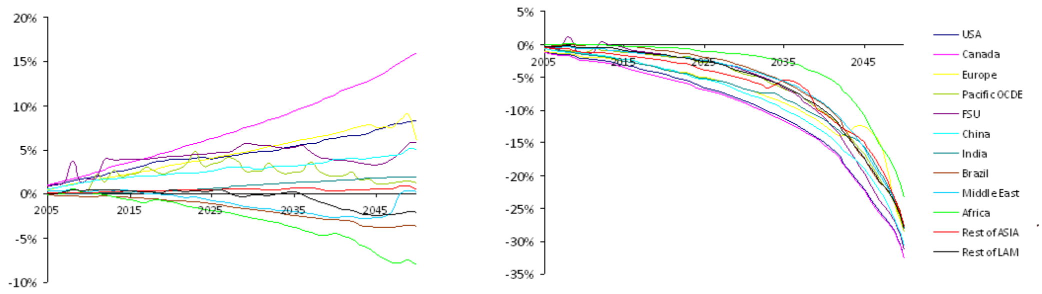

Figure 4.8: Regional percentage change of yield (left graph) and land rent (right graph) between the reference case and the climate and CO_2 effects case

lower with the climate and CO_2 fertilisation effect than in the reference scenario, explaining the drop in land rent.

Figure 4.9 also shows that in comparison with the reference scenario, the trade balance of Northern regions improves with climate change and the CO_2 fertilisation effect while the trade balance of Africa, Brazil and the rest of Latin America deteriorate. Therefore, the increase of CO_2 concentration could lead to a relocation of agricultural production from Southern regions – Africa, Brazil and the rest of Latin America – to Northern ones, mainly in Canada, USA and the FSU. This results in an increase in production in Canada, USA, and the FSU by respectively 13%, 6% and 5% and to a fall in Africa, Brazil and Rest of Latin America by respectively 8%, 3.2% and 2%.

4.5 Conclusion

Two prospects for the development of the Nexus Land-Use have been presented in this chapter. The first one relates to the coupling with the Imaclim-R model whose purpose is to incorporate the land constraint in a general equilibrium structure. In the assessment of mitigation policies, biomass energy appears to be an advantageous option to stabilise emissions. However, the simulations carried out by the Nexus Land-Use reveal that such scenarios lead to significant increase in land rent, which is not fully taken into account in the Imaclim-R agricultural price. To improve this point, a methodology is provided to incorporate the land cost calculated by the Nexus Land-Use into the Imaclim-R model. The impact of land rent variations on the GDP will largely depend on its redistribution within the economy. Such a redistribution is driven both by tax system and market mechanisms. For this

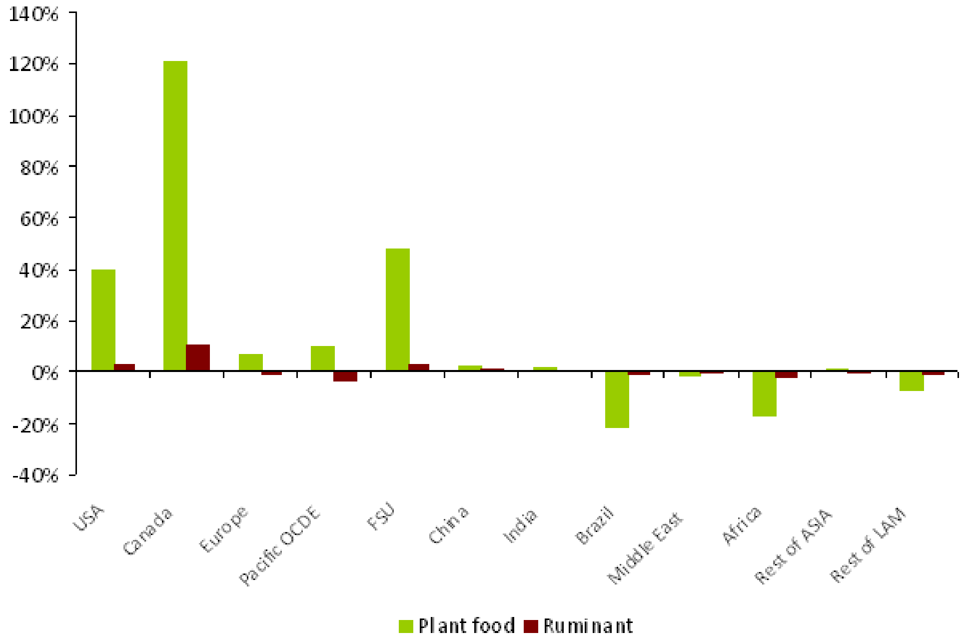

Figure 4.9: Variation of the regional trade balances-to-consumption ratio of plant food and ruminant between the reference case and the climate and CO_2 effects case

reason, the demand side of agricultural market must be refined as well, and the mathematical form of the food demand system must be appropriately chosen.

Two additional issues must also be highlighted. First, the distributional impact of food price variations must be carefully analysed. Costs of food price increases are actually much higher for poorer people, who may be plunged them into famine. Reasoning on averages could therefore hide important losses and skew results. Then, it is important to refine the calculation of agricultural emissions to account for non-CO_2 gases – CH_4 and NO_2 – that are largely emitted by agriculture, and to validate the carbon neutrality assumption of biomass, which can be questionable for large-scale production.

The second prospect concerns the coupling of the Nexus Land-Use to the vegetation model ORCHIDEE. Including crop yield variations simulated by ORCHIDEE with a climate change scenario in the Nexus Land-Use provides a picture of the agricultural system in 2050 that contrasts with a reference case where the climate and CO_2 effects are not accounted for. By comparison with this reference case, the global increase in crop yields due to climate change and to the CO_2 effect generates a decrease in food prices. This results in a profit reduction, and in corollary way, in an increase in consumers' surplus. This conclusion contrasts with traditional assessments of the impact of climate change on agriculture, which did not take into account those latter benefits. However, this study does not consider the probable rise of climate variability resulting from anthropogenic changes. This effect could dramatically reduce benefits for consumers, as increases in the number of years with poor yields should raise important issues in terms of food security. According to our results, another important consequence of climate change and of the CO_2 effect is the relocation of agricultural production from Southern regions – Africa, Brazil and Rest of Latin America – to Northern ones, mainly in Canada, USA and FSU.

Table 4.4: Regional evolutions of the potential yield due to climate change and CO_2 fertilisation effect, proportion of crop in the total regional production and aggregate coefficient of potential yield evolution used in the Nexus Land-Use

	Wheat		Maize		Millet & Sorgho		
Regions	δ_{cc}^{Wheat}	% Wheat	δ_{cc}^{Maize}	% Maize	δ_{cc}^{Trop}	% Trop	δ_{cc}
USA	13.00%	14.08%	13.50%	60.35%	15.90%	1.10%	10.18%
Canada	10.50%	54.59%	80.30%	17.24%	110.80%	0%	19.57%
Europe	11.80%	57.64%	22.50%	24.78%	28.20%	0.07%	12.40%
Jap./Aus./NZ	10.30%	58.2%	11.9%	1.38%	10.20%	1.83%	6.34%
FSU	12.40%	66.93%	37.90%	17.22%	47.50%	0.67%	15.14%
China	15.80%	23.68%	11.20%	25.72%	14.50%	0.97%	6.76%
India	17.50%	22.68%	-1.75%	5.64%	-8.17%	8.07%	3.21%
Brazil	4.50%	2.52%	-3.71%	33.42%	1.30%	0.00%	-1.13%
Middle East	12.70%	77.55%	-1.27%	5.09%	-8.91%	1.74%	9.63%
Africa	10.40%	11.49%	-2.37%	24.18%	0.60%	18.25%	0.73%
Rest of Asia	10.20%	9.77%	10.80%	10.72%	18.20%	0.42%	2.23%
Rest of LAM	11.90%	15.65%	0.10%	37.62%	0.70%	3.02%	1.92%

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Conclusion

While they were one of the main focus of earlier economics, agriculture and land-use have progressively attracted less interest in favour of the industrial and services sectors. In spite of their declining role in economic growth, land-intensive sectors remain one of the major drivers of anthropogenic changes. The combined effect of rapid demographic evolutions and depleting fossil fuel, both spurring an increased demand for biomass, will probably accentuate the environmental impact of land-use changes in the coming decades. This relationship has motivated renewed efforts to understand and model agriculture and land-use dynamics.

These efforts mainly focus on the representation of global drivers that drive land-use changes. With the emergence of transboundary environmental problem, such as climate change, and the intensification of international trade linked to the globalisation of the world economy, land-use modelling must be rethought. Indirect land-use changes (ILUC) are an enlightening example as it shows that changes in production or consumption pattern in one region of the world can induce land-use change in other regions through international exchanges. Modelling such indirect effects is a challenging task as this requires a comprehensive analysis of the mechanisms at play, from consumption behaviours to production constraints. In spite of significant progress in the process representation, it appears that models do not manage yet to converge towards a robust estimation of ILUC. In particular, there is no consensus on two crucial mechanisms of ILUC that are the crop yield response to food price and the price-elasticity of demand for food. However, it should be noted that a fine inquiry on the sources of disagreement between models is difficult because their structures are less transparent as they become increasingly sophisticated.

More fundamentally the question regarding the appropriate use of models arises. Their added value is to provide a consistent vision of the studied sector by combining complex equations and various database. In this extent, they are able to represent interconnections between mechanisms at different levels and to shed light on potential unintuitive system effects, such as indirect land-use changes. However, to build their coherent framework, each model relies on a theoretical structure and on several subjective assumptions. Consequently, one should not expect robust predictions from models but rather policy assessments guaranteeing internal consistency (Peace and Weyant, 2008).

The land-use model presented in this thesis has been developed based on some of these lessons. It aims at describing land-use dynamics with a high level of consistency by combining biophysics and economics into a single modelling framework. In addition, multi-scale effects are represented by incorporating local heterogeneity into a global architecture. For a relevant use, an extensive description of the model is provided and its limitations are exposed and discussed. Among them, it emerges that the theoretical basis from Ricardian inspiration does not completely match the reality and necessitates the addition of a residual land category to the model. This theoretical limitation can be related to the fact that the economics of land-use still heavily relies on the Ricardian and von Thünen theories (Parks and Hardie, 2003), developed in the XIXst century. Given recent evolutions of land-use dynamics, further land-use modelling should be accompanied by renewed theoretical development.

In spite of these limitations, the methodology undertaken herein presents several advantages. First, the modelling of a Ricardian frontier of production and the incorporation of regional land area distributions of potential yields make it possible to represent from models the yield variations induced by the expansion of cropland on marginal lands. In addition, the representation of intensification process both for food crops and livestock production enables a corresponding analysis of changes in diet and caloric origin (animal and plant). Finally, the integration of biophysical limits into an economic framework allows us to highlight non-linear effects that appear in the most constrained scenarios.

This modelling tool was then used to test the influence of global drivers on agriculture and land-use: globalisation (chapter 3) and climate change (chapter 4). Among the numerous and complex mechanisms by which globalisation could potentially impact the food and agricultural system, this study concentrated on the lifestyles convergence and the subsequent shifts in food diets. As suggested by Lambin et al. (2001), the analysis shows that globalisation amplifies or attenuates the driving forces of land-use change through the diet channel. The Nexus Land-Use modelling framework makes it possible to identify some of the mechanisms of amplification or mitigation. Among them, the consumption of animal products appears to be a central component. Because the livestock production process is particularly land-intensive, meat and milk consumption has a stronger impact on agriculture than plant food consumption. In addition, in the scenarios converging the most towards Western lifestyles, the production system catches up with its biophysical asymptotes – in terms of availability of high quality lands and potential crop yield – triggering non-linear effects that amplify some more the rise of calorie price, the consumption of fertilisers and pesticides, and the expansion of intensive agriculture. In addition to these findings, numerous insights emerge from the sensitivity analysis on the main assumptions. First, the consequences of agrofuel development and reducing deforestation policies on agriculture are all the greater than the proportion of animal calories in food diets is large. Hence, reorienting dietary habits toward plant food calories appears to be necessary to reduce the potential negative effects of agrofuel and forest preservation policies. Reducing trade distortions contribute to reduce the tensions on land-use, but entail some detrimental local effects such as concentrating the production in tropical regions with rich biodiversity- and carbon-content. Furthermore, trade intensification increases the possibility of leakage or indirect effects and may complexify land-use analysis. This chapter finally reveals that enhancing the productivity of pastures could be a promising avenue to reduce tensions on land-use.

Climate change is the second global driver that was analysed. To this end, two work prospects were presented. The first one is the coupling to the Imaclim-R model (Sassi et al., 2010). According to its results, biomass energy appears to be an advantageous option to stabilise emissions. However, the simulations carried out by the Nexus Land-Use reveal that such scenarios lead to significant rise of land rent, that is not fully taken into account in the Imaclim-R agricultural price. To address this point, a methodology is provided to incorporate the land rent calculated by the Nexus Land-Use into the Imaclim-R model. Insights are also provided in the form of the food demand function, that appears to be a determinant factor of the land rent redistribution within the economy. The distributional impact of food price variations appears also to be a key question. Indeed, costs of increases in food prices are much higher for poorer people who may be plunged into famine. Reasoning on averages would therefore hide important losses and skew results.

The second development prospect relates to the coupling to the ORCHIDEE model (Krinner, 2005). Including in the Nexus Land-Use crop yield variations simulated by this vegetation model with a climate change scenario provides interesting insights on world agriculture in 2050. It appears that with the global rise of crop yield, the land rent diminishes at the expense of the producers but for the benefit of consumers. This conclusion contrasts with traditional assessments of the impact of climate change on agriculture that did not take into account those latter benefits. However, this study does not consider the probable rise of climate variability resulting from anthropogenic changes. This effect could dramatically reduce benefits for consumers, as increases in the number of years with poor yields should raise important issues in terms of food security. Another consequence of yield variations in response to the rise of CO_2 concentration is the relocation of agricultural production from Southern regions – Africa, Brazil and the rest of Latin America – to Northern ones, mainly in Canada, USA and the Former Soviet Union.

Advances in land-use science of this thesis are mainly methodological. This work shows how various available models and databases can be combined to study how economic and biophysical dynamics interact in land-use, and how these dynamics can be influenced by external drivers. In particular, this study brings light on the way global forces may reshuffle the cards of agriculture and land-use. Thanks to its global scope and to its functioning at an aggregated level, the Nexus Land-Use has proven its ability to account for such forces. Rise of uncertainty and complexity, relocation of production and change of its conditions are some of the many consequences of globalisation and climate change.

The model presented here is at its first step of development and several paths of improvement are possible. First, emissions calculation must be incorporated to assess the role of non-CO_2 greenhouse gases and to compare trajectories based on deforestation with those based on intensification.

Secondly, one could endogenise some of the external drivers of the model. Even if they may result in a large extent from political decisions, it would be interesting to compare policies with trajectories based on farmers optimal decisions. For example, an endogenous representation of deforestation mechanisms would allow for more detailed evaluation of food and biomass energy scenarios. In the same way, a modelling of the bioenergy sector would give more insights on the impact of higher oil prices on agriculture and land-use.

Variability and dispersion effects are another element to take better account of. The consequences of an increase in food prices are not the same whether it is gradual or sudden, since market actors will have difficulty planning ahead and adjusting to the fluctuating market signals. In addition, higher food price will have a stronger impact on poorer people as previously stressed. Food markets modelling in the different regions of the Nexus Land-Use including data on income distribution will enable to represent such effects. In the same way, climate variability is an important factor to correctly assess the impact of climate change on the food and agricultural system (see *supra*) and could be usefully included in our modelling.

Finally, the couplings to Imaclim-R and ORCHIDEE will be the basis for meeting the ambition of providing a model around which the dialogue between the different components of integrated assessment models is possible. The value of the land rent will be a key component of this dialogue, as it links the socio-economic and the biophysical spheres by providing insights on the tensions on the biophysical system spurred by the various options regarding food, bioenergy or deforestation policies.

Appendix: Model evaluation

To assess the validity of the methods and assumptions implemented in the Nexus Land-Use, we run the model from 1990 to 2006 (last date for which actual data on the supply-use biomass balance from the Agribiom database are available) and compare its outcomes to the actual land-use reported by Ramankutty and Foley (1999). Results are provided on figure 4.10.

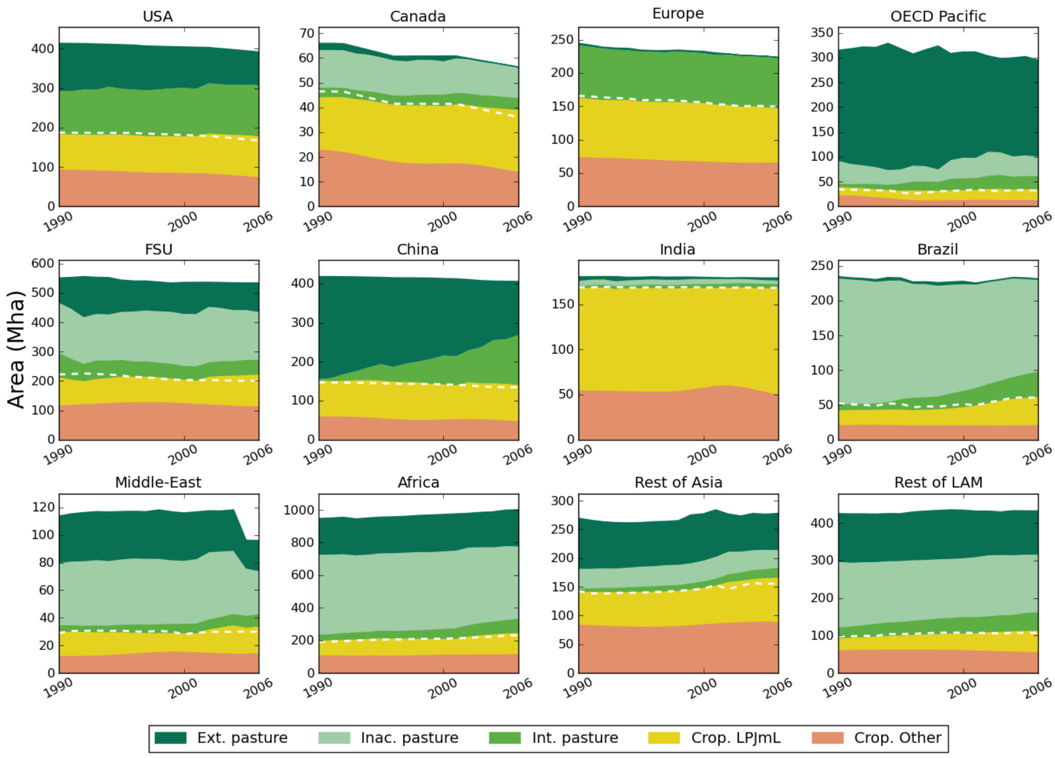

Figure 4.10: Nexus Land-Use simulations over the period 1990-2006 against actual land-use reported by Ramankutty and Foley (1999) (white dotted line)

For this simulation, we use retrospective data on biomass consumption from

(Dorin, 2011) and the evolution of agricultural area from Ramankutty and Foley (1999). Potential yields are supposed to be constant over all the simulation period, assuming implicitly no degradation of land and no genetic or agronomic progress over the 1990-2006 period. The regional evolutions of fertliser price index are taken from the World Bank.

The model error on the pasture to cropland ratio amounts globally to 3% on average per year. This global figure covers some regional discrepancies. While for most countries, the error is below 9% on average per year, model performances are less satisfactory for Brazil, Pacific OECD and Canada where the error amounts respectively to 11%, 12% and 10% on average per year.

This result is not surprising for Brazil as the Nexus Land-Use theoretical framework was seen to be less adapted to this country due to its important market imperfections (see Chapter 2). In the long term, we expect that these imperfections will progressively disappear under the effect of a greater pressure on land-use spurring farmers to rationalise their production. Agricultural surfaces in Canada are relatively low (41 Mha of cropland and 19 Mha of pasture in 2001), so if the relative error appears to be large, in absolute terms, the gap with the actual land-use is in fact small. Finally, the poor performance for the Pacific OECD can be explained by a bias related to the aggregation in a same region of Australia and Japan which are characterised by very contrasted agricultural practices (notably concerning the use of chemical inputs).

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