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

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**Abstract**

Interactions between food demand, biomass energy and forest preservation are driving both food prices and land-use changes. This study presents a new model called Nexus Land-Use which describes these interactions through a representation of agricultural intensification. The model combine biophysics and economics to calculate crop yields, food prices, and resulting pasture and cropland areas within 12 inter-connected regions. The representation of cropland production systems relies on a biomass production function derived from the crop yield response function to inputs and a spatially explicit distribution of potential crop yields prescribed from the Lund-Postdam-Jena global vegetation model for managed Land (LPJmL). The economic principles governing decisions about land-use and intensification are adapted from the Ricardian rent theory, assuming cost minimisation. The land-use modelling approach described in this paper makes it possible to explore interactions among different types of demand for biomass, including indirect effects on land-use change resulting from international trade. Yield variations induced by the possible expansion of croplands on less suitable lands are modelled by using regional land area distributions of potential yields, and a boundary between intensive and extensive production. Idealized scenarios exploring the impact of forest preservation policies or rising energy price on agricultural intensification are presented.

## 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

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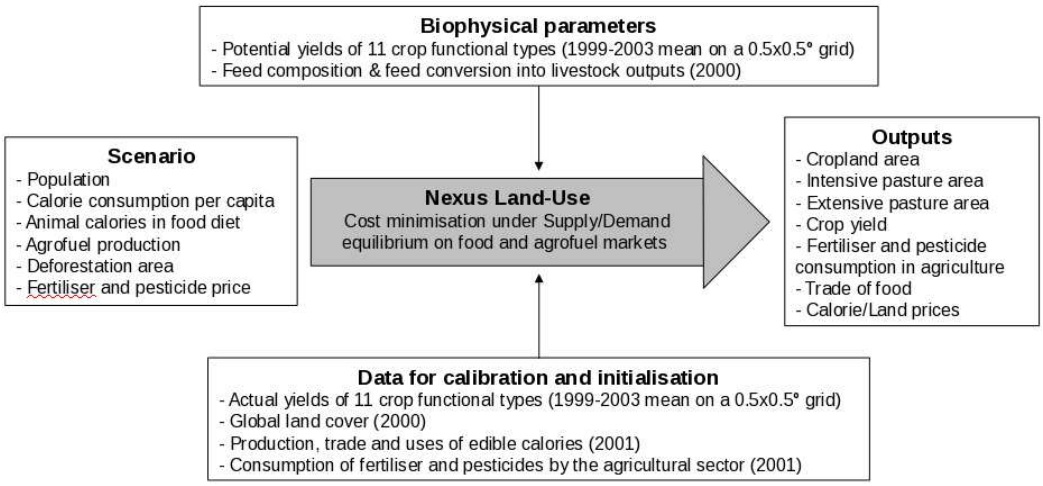



Figure 1: Description of the modelling system. "Fertiliser and pesticide consumption" includes also other consumption of chemical and mineral goods.

demand for services provided by a finite system may generate tensions on natural resources. To avoid rivalry between multiple demands, decisions related to land-use must take several elements into consideration. 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 process. 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.

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 process (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 availability, and plant growth at a detailed ge-

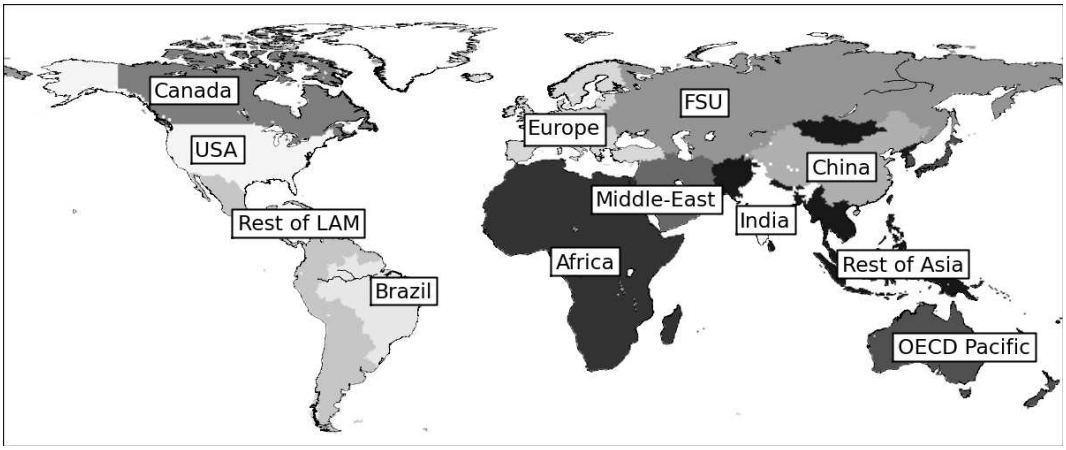



Figure 2: Nexus Land-Use regions. OECD Pacific includes Australia, New Zealand, Japan and South Korea. FSU stands for Former Soviet Union and Rest of LAM for Rest of Latin America

ographic 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 paper 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 paper 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, table 1), and 5 land-use types: forests, croplands (2 types), and pastures (2 types). The model drivers are the calorie consumption per capita, the share of animal products in food consumption, agrofuel consumption and evolution of forest areas (figure 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 Scope and principles of the model

## 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 the food demand, considering that it is prescribed.

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 toward the potential yield.

Such a modelling strategy implies that among the four main productions 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 energy-related issues, including or not the effect of carbon pricing, and of course with land-use-related issues, 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 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.

In the view to exploring different pathways, this assumption could be relaxed in future development of the model.

## 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 toward 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 $D^{fc}_{agrofuel}$, 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 (1-3) and plant food calories (4-7). Demand for land $D_{surf}$ resulting from this equilibrium must be

equal to the land supply $S_{surf}$ (8):

$$
\begin{aligned}
Q_r &= (D_h^r + Exp^r - Imp^r)(1+\omega_{swof}^r) && (1)\\
Q_{r,ext} &= D_{surf}\rho_{past}^{r,ext}\int (f_j^{Pext} + f_j^{Pres})dj && (2)\\
Q_{r,int} &= Q_r - Q_{r,ext} && (3)\\
D_{r,int}^{fc} &= Q_{r,int}\beta_{r,int}\phi_{r,int}^{fc} && (4)\\
D_m^{fc} &= (D_h^m + Exp^m - Imp^m)(1+\omega_{swof}^m)\beta_m\phi_m^{fc} && (5)\\
D^{fc} &= D_h^{fc} + D_m^{fc} + D_{r,int}^{fc} + D_{agrofuel}^{fc} + Exp^{fc} - Imp^{fc} && (6)\\
Q_{other\ crop}^{fc} + D_{surf}\int f_j^{crop}\rho_j dj &= D^{fc}(1+\omega_{swo}^{fc}) && (7)\\
S_{surf} &= D_{surf} && (8)
\end{aligned}
$$

The ruminant production $Q_r$ is deduced from equation 1. Seed ($s$), waste ($w$) at the farm level and other uses ($o$) are added by using coefficients $\omega_{swo}^{fc}$ for food crops, $\omega_{swof}^r$ for ruminants and $\omega_{swof}^m$ for monogastrics (see section 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 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). The demand for feed to produce ruminant $D_{r,int}^{fc}$ or monogastric $D_m^{fc}$ calories is deduced from equations 4 and 5 using the conversion factors $\beta_{r,int}$ and $\beta_m$ and the feed composition factor $\phi_{r,int}^{fc}$ and $\phi_m^{fc}$ (see section 3.3). Equation 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 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 9.

### 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 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 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 3, see section 5.1 for more details). Demand for each of these four categories is forced by exogenous scenarios (figure 1).

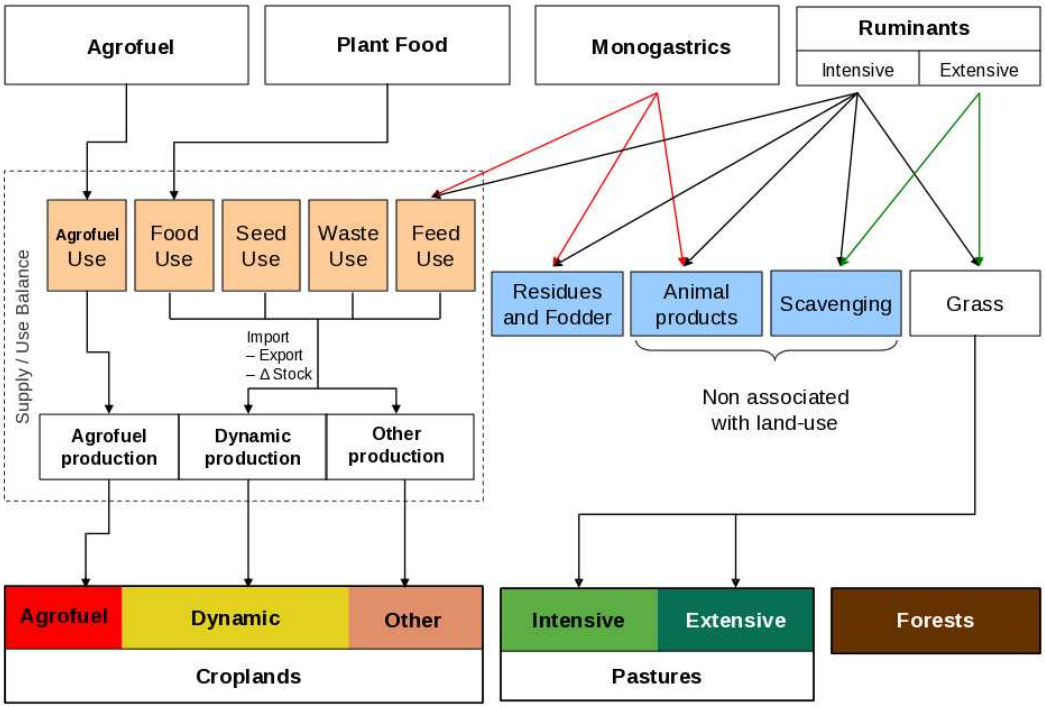



Figure 3: Links between food and agrofuel demand and land-use.

Agrofuels are represented separately and will be the subject of a future publication. 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 3.3.

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 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 3.1). The resulting production accounts for 75% of global food crops calorie production given by Agribiom (table 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 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.

# 3 Modelling agricultural intensification and biophysical constraints

## 3.1 Land area classes of potential yields

### 3.1.1 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 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) $\alpha a$, 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].

### 3.1.2 Actual yields computation in LPJmL

CFT actual yields $y_{CFT,l}^{actual}$ 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, $\alpha a$ 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 where 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.

### 3.1.3 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 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.

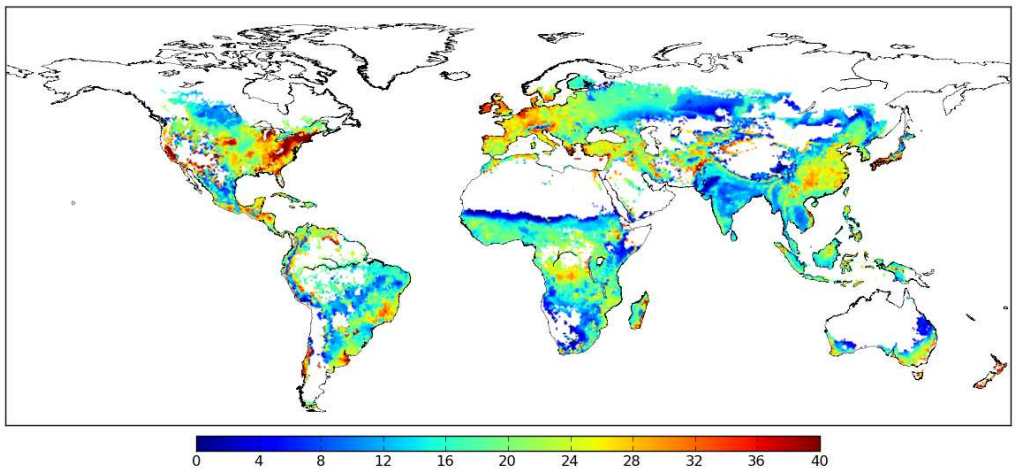



Figure 4: Representative potential yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

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

$$y_l^{max,agg} = \frac{\sum_{CFT} \; y_{CFT,l}^{max} \times f_{CFT,l} \times cal_{CFT}}{\sum_{CFT} \; f_{CFT,l}} \tag{9}$$

It is displayed in figure 4. The representative actual yield is computed likewise and its spatial distribution is displayed in figure 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:

$$S_j^{crop} = \sum_{l, \tilde{\rho}_j^{max} < y_l^{max,agg} < \tilde{\rho}_{j+1}^{max}} S_l \times \left( \sum_{CFT} f_{CFT,l} \right) \tag{10}$$

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 $\rho_j^{max}$ of land class $j$ is the mean of the potential yield in all all grid points belonging to class $j$:

$$\rho_j^{max} = \frac{\sum_{l, \tilde{\rho}_j^{max} < y_l^{max,agg} < \tilde{\rho}_{j+1}^{max}} \; y_l^{max,agg} \times (\sum_{CFT} \; f_{CFT,l}) \times S_l}{S_j^{crop}} \tag{11}$$

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 $\rho_j^{actual}$ are computed. We also calculate a representative potential yield on each grid point in case pasture or forests are converted to cropland (figure 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

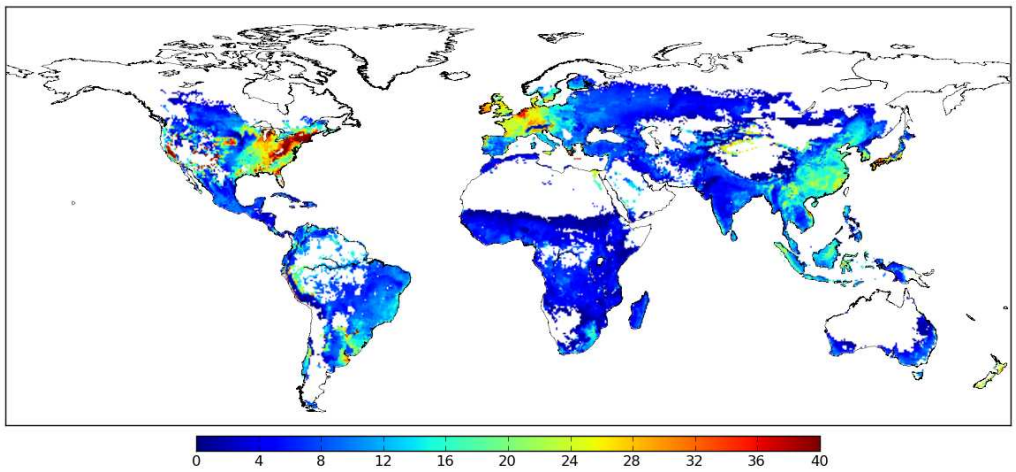



Figure 5: Representative actual yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

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 2.3 for more details on dynamic and other croplands).

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 6 and 7).

### 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 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 $\rho_j^{max}$ 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 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

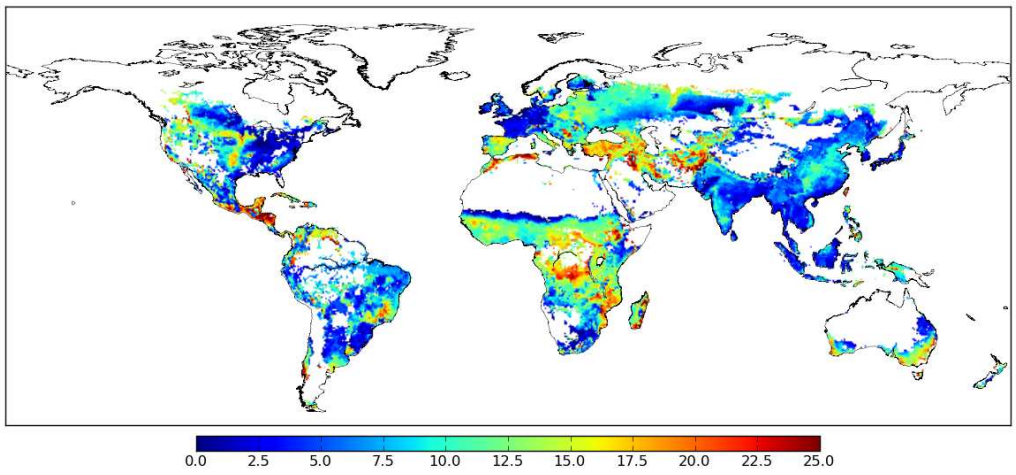



Figure 6: Difference between potential and actual yield of crops modelled in the LPJmL model ("dynamic crops") in Mkcal/ha/year (average over the 1999-2003 period).

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:

$$\rho_j(IC_j) = \rho_j^{max} - (\rho_j^{max} - \rho_j^{min}) \frac{\alpha_{IC}(\rho_j^{max} - \rho_j^{min})}{IC_j + \alpha_{IC}(\rho_j^{max} - \rho_j^{min})} \tag{12}$$

where the minimum yield $\rho_j^{min}$ is the y-intercept, defined as the no-inputs yield. Its value is set to ten percent of the potential yield $\rho_j^{max}$. 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 9). However it may lead to an underestimation in temperate regions (Thierry Doré, pers. com.).

From an economic point of view, equation 12 is a production function representing the technical relationship between a quantity of output (yield) and a combination of inputs (fertilisers and pesticides).

### 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 $\beta$ defined as the calories of feed needed to produce one calorie of animal food, and feed composition factors denoted $\phi$ defined as the share of each specific feed category in total feed. Feedstock categories are detailed in section 2.3. $\beta$ and $\phi$ 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 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.

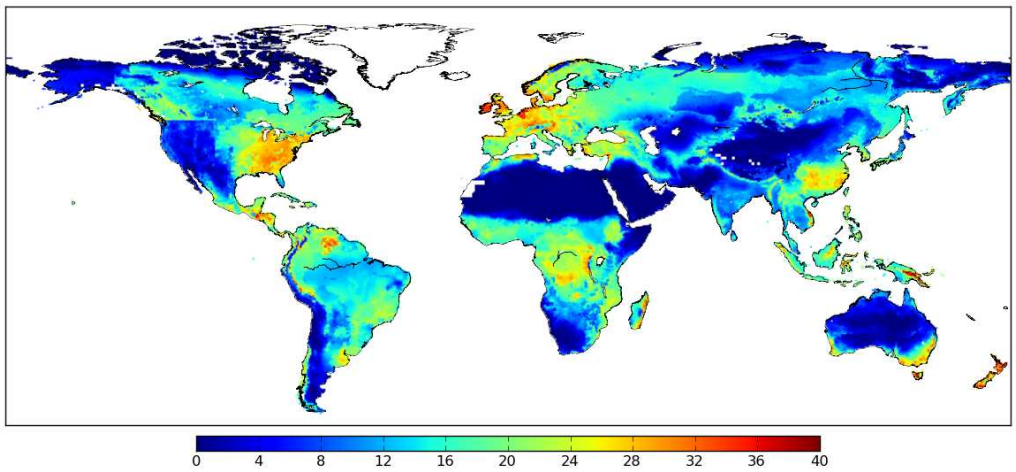



Figure 7: Potential yield computed with national crop repartitions in rainfed conditions (Mkcal/ha/yr) (average over the 1999-2003 period).

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, ruminants are fed with 13% of food crops, 33% of residues and fodder crops and 53% of grass (see table 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 unreliable, in particular for Brazil and Asia. Nevertheless, several fodder crops are also included in the LPJmL CFTs (see table 3), and some areas for fodder production are included in the Ramankutty et al. [2008] cropland

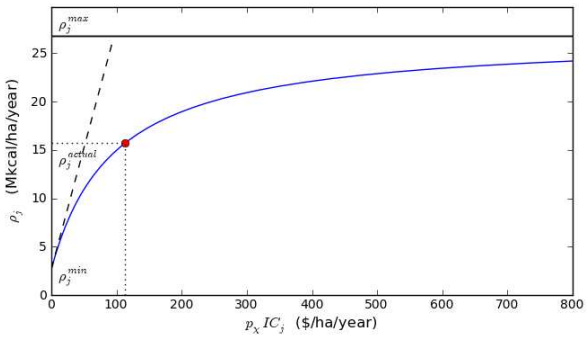



Figure 8: Yield in a land class as a function of chemical input consumption $IC_j$. $\rho_j^{max}$, $\rho_j^{actual}$ and $\rho_j^{min}$ are the potential, actual and minimum yields of the land class $j$. $p_\chi$ is the price index of chemical inputs.

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.

### 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 3.1.

Based on the distinction between the extensive and intensive livestock production 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 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 12 and 13).

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

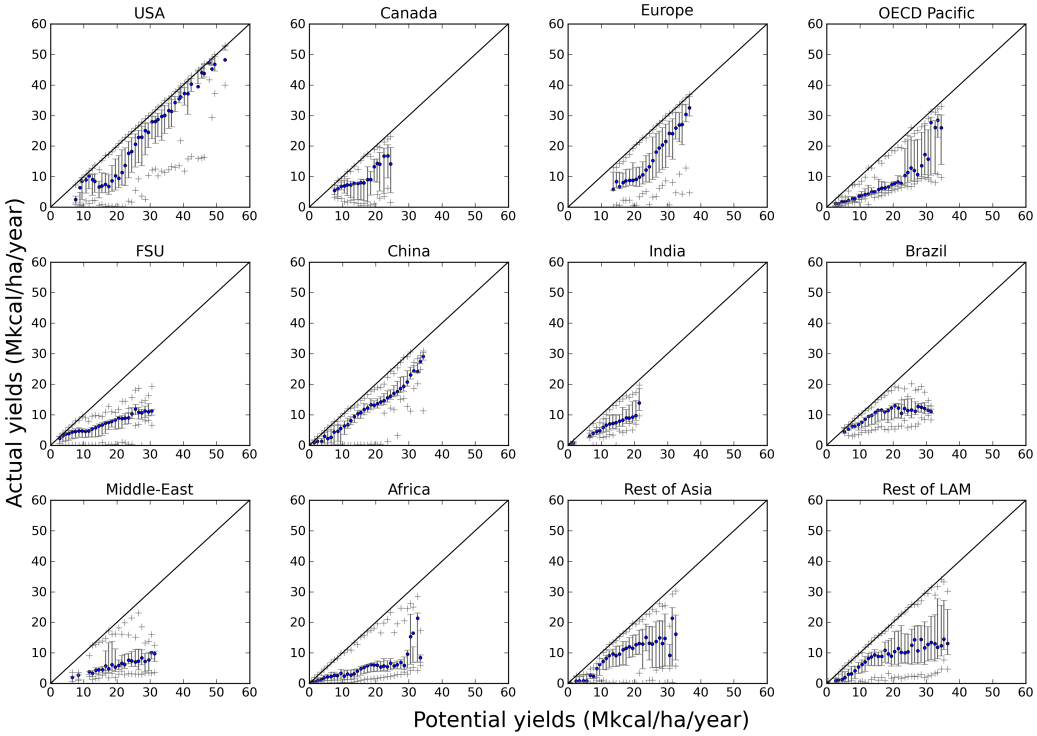



Figure 9: Actual yield versus potential yield of dynamic crops within each potential yield class. Crosses are minimums and maximums, whiskers go from the 20th to the 80th percentile. See figure 6 for a map of the difference between potential and actual yields of dynamic crops.

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].

# 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 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.

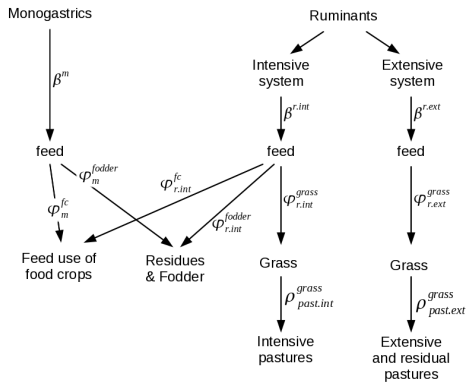



Figure 10: Links between animal calorie production, feed categories and pasture areas. Reading: the amount of feed required to produce one calorie of monogastric is $\beta_m$, split into a share $\phi_m^{fc}$ of food crops and $\phi_m^{fodder}$ of crop residues and fodder. Values are reported in tables 4, 5 and 6

## 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 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 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 3.2 and shown in equation 12. It presents the following mathematical form:

$$IC_j(\rho_j) = \alpha_{IC}(\rho_j^{max} - \rho_j^{min}) \left( \frac{\rho_j^{max} - \rho_j^{min}}{\rho_j^{max} - \rho_j} - 1 \right) \tag{13}$$

- $p_\chi$ 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 $\alpha_{IC}$ (in \$/Mkcal) is detailed in section 5.2.

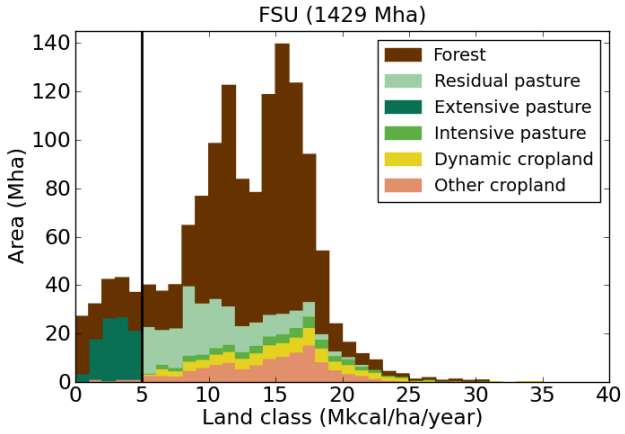



Figure 11: Illustration of the production frontier (limit land class $j_{limit}$) on the histogram of the land area classes of potential yield in the Former Soviet Union (black vertical bar).

## 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 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 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 3.4.

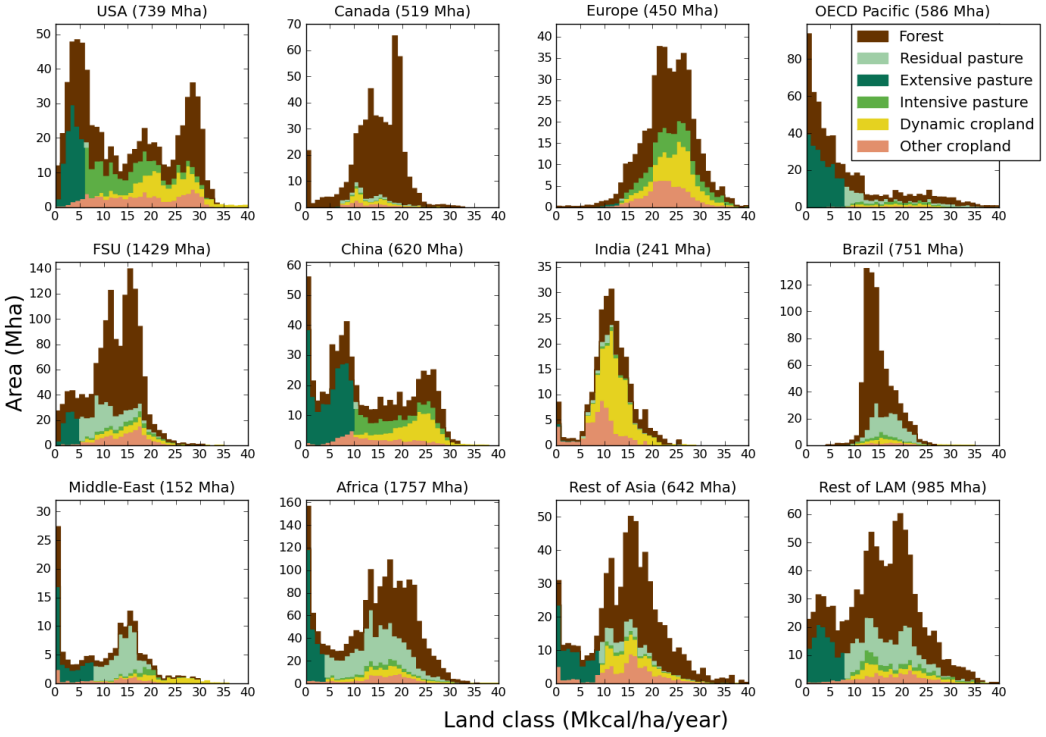



Figure 12: Histogram of the land area classes of potential yield in the 12 Nexus Land-Use regions at the base year.

### 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:

$$\underset{\substack{\rho_j, j_{limit}, D^{fc}_{r,int} \\ Q_{r,int}, Q_{r,ext}, D_{surf}}}{Min} \left( \int_{j_{limit}}^{j_{max}} (p_\chi IC_j(\rho_j) + FC_{tot}) f_j^{crop} dj \right) D_{surf} \tag{14}$$

$$Q^{fc}_{other} + \int_{j_{limit}}^{j_{max}} f_j^{crop} \rho_j dj D_{surf} = (D^{fc}_{r,int} + D^{fc}_{h+m+agro})(1 + \omega^{fc}_{swo}) \tag{15}$$

$$Q_r = Q_{r,int} + Q_{r,ext} \tag{16}$$

$$Q_{r,ext} = \left( \int_0^{j_{limit}} f_j^{Pext} dj + \int_{j_{limit}}^{j_{max}} f_j^{Pres} dj \right) \rho^{r,ext}_{past} D_{surf} \tag{17}$$

$$Q_{r,int} = \frac{D^{fc}_{r,int}}{\beta_{r,int} \phi^{fc}_{r,int}} \tag{18}$$

$$S_{surf} = D_{surf} \tag{19}$$

Variables are defined in section 2.2 and in table 9. As a reminder, all variables of this program are regional. Equations 15 to 19 display the constraints of the minimisation pro-

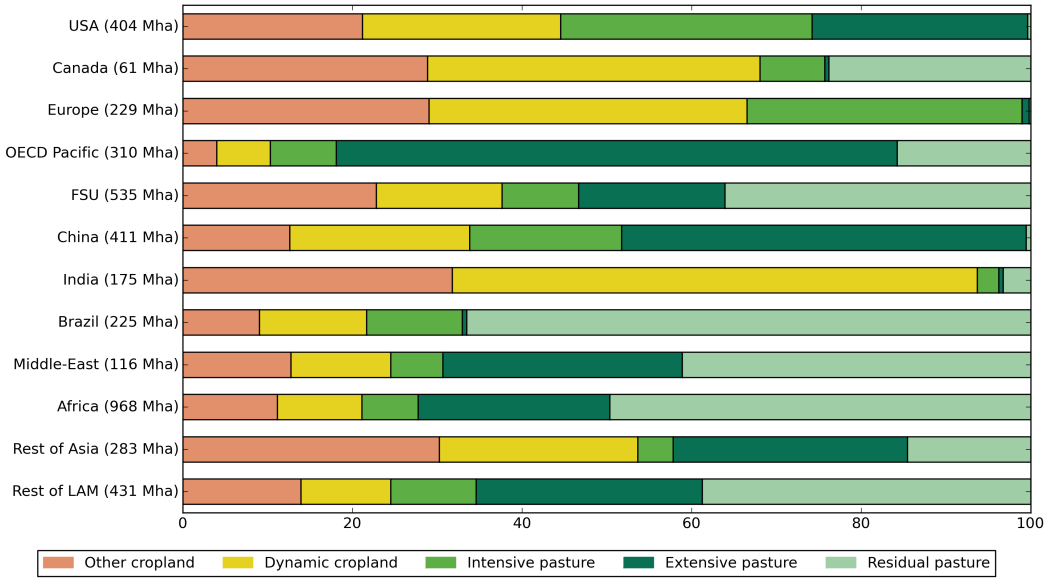



Figure 13: Share of different agricultural land-use types in the 12 regions of the model at the base year.

gram. Equation 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 16 corresponds to the constraint on global ruminant production. Equation 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 5.4). Equation 18 is the constraint on the intensive ruminant production from feed. Finally equation 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 $\rho_j$ 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:

$$p_{cal} = p_\chi IC'_j(\rho_j) \tag{20}$$

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:

$$p_r = p_{cal}(1+\omega^{fc}_{swo})\beta_{r,int}\phi^{fc}_{r,int} \tag{21}$$

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 $j_{limit}$:

$$(p_{cal}\rho_{j_{limit}} - p_\chi IC_{j_{limit}}(\rho_{j_{limit}}) - FC_{tot})f^{crop}_{j_{limit}} + p_r f^{Pres}_{j_{limit}}\rho^{r,ext}_{past} = p_r f^{Pext}_{j_{limit}}\rho^{r,ext}_{past} \quad (22)$$

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 22 holds.

To simplify the resolution, the fractions $f^{crop}_{j_{limit}}$, $f^{Pres}_{j_{limit}}$ and $f^{Pext}_{j_{limit}}$ in equation 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 19 can be interpreted as the shadow price of land. Finally, the expression of land rent denoted $\lambda$ is the following:

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

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.

### 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 ($\phi^{fodder}_{m,k}$) is small. Yet, in the Nexus Land-Use modelling framework – where residues and fodder are considered to be free – the higher the $\phi^{fodder}_{m,k}$ 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 $p^w_{cal}$ defined as follows:

$$p^w_{cal} = \sum ShareExp_k \times p_{cal_k} \tag{23}$$

where $ShareExp_k$ is the export share of region k in the pool. It is set equal to $\frac{\alpha_k^{exp} p_{cal_k}^{-2}}{\sum_k \alpha_k^{exp} p_{cal_k}^{-2}}$. Import and export functions for region k are thus given by:

$$Imp_k^{fc} = \alpha_k^{imp} \times \frac{p_{cal_k}}{p^w_{cal}} \times D_k^{fc} \tag{24}$$

$$Exp_k^{fc} = \frac{\alpha_k^{exp} p_{cal_k}^{-2}}{\sum_k \alpha_k^{exp} p_{cal_k}^{-2}} \times \sum_k Imp_k^{fc} \tag{25}$$

$$\tag{26}$$

$\alpha_k^{exp}$ and $\alpha_k^{imp}$ are regional coefficients calibrated on actual import and export volumes from the Agribiom database in 2001. 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.

### 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 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 1 to 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:

$$\sum_j f_j^{Pint} D_{surf} \rho_{past,int}^{grass} = Q_{r,int} \beta_{r,int} \phi_{r,int}^{grass} \tag{27}$$

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.

# 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 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.

## 5.1 World supply and use of crop calories

Each year, the Nexus Land-Use model calculates a global biomass balance (figure 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 paper. 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 FAOSTAT [2010] provides annual country-level Supply-Utilization Accounts (SUA) in metric tones (table 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, 2010], but without a "Processed" column on the right side:

$$Q^i_{AB} - Exp^i_{AB} + Imp^i_{AB} + \delta^i_{stock,AB} = D^i_{h,AB} + Feed^i_{AB} + Seed^i_{AB} + Waste^i_{AB} + Other^i_{AB} \quad (28)$$

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 + $\Delta$Stocks) 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 $\omega^{fc}_{swo}$ and is defined in (29). Corresponding coefficients for monogastrics and ruminants are $\omega^{m}_{swof}$ and $\omega^{r}_{swof}$ which also accounts for feed use (whey, bone and fish meal, etc.).

$$\omega^{fc}_{swo} = \frac{Seed^{fc}_{AB} + Waste^{fc}_{AB} + Other^{fc}_{AB}}{D^{fc}_{h,AB} + D^{fc}_{feed,AB} + Exp^{fc}_{AB} - Imp^{fc}_{AB}} \quad (29)$$

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 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.

$$Q^{fc}_{feed,2001} = Q^{AB}_{m}\beta_m\phi^{fc}_{m} + Q^{2001}_{r,int}\beta_{r,int}\phi^{fc}_{r,int} \quad (30)$$

As previously mentioned in section 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 31, as given by:

$$Q^{fc}_{dyn\ crop} + Q^{fc}_{other\ crop} = (D^{fc}_{h,AB} + D^{fc}_{feed,2001} + Exp^{fc}_{AB} - Imp^{fc}_{AB})\omega^{fc}_{swo} \quad (31)$$

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

## 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 $\alpha_{IC}$ 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 3.2), implies that the yield value minimizing farmers' cost is proportional to the potential yield values over each land class.

$$\frac{\rho_j(p_{cal})}{\rho^{max}_j} = 1 - (1 - 0.1)\sqrt{\frac{\alpha_{IC} \times p_\chi}{p_{cal}}} \quad (32)$$

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:

$$\sum \rho_j f^{crop}_j S_{surf} = \sum \rho^{actual}_j f^{crop}_j S_{surf} \quad (33)$$

To assess the validity of the resulting distribution of yields over land classes, correlation coefficients between computed base year yields $\rho_j$ and actual yields $\rho^{actual}_j$ 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 $\alpha_{IC}$:

$$IC'_j(\rho_j) = \alpha_{IC}\left(\frac{\rho^{max}_j - \rho^{min}_j}{\rho^{max}_j - \rho_j}\right)^2 = \frac{p_{cal}}{p_\chi} \quad (34)$$

$$\sum_j p_\chi IC_j(\rho_j) f^{crop}_j S_{surf} = IC_\chi \quad (35)$$

Equation 34 results from the first order conditions for cost minimisation (see section 4.3). In equation 35, the sum of the intermediate consumption of each land class is set equal to the intermediate consumption from $IC_\chi$ coming from the GTAP 6 database [GTAP, 2006]. $IC_\chi$ is the regional consumption of the part of the agricultural sector modelled in LPJmL from the chemical and mineral sectors (table 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 8.

### 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 4.3 equation 22). This yields:

$$FC_{tot} = p_{cal}\rho_{j_{limit}} - p_{\chi}IC_{j_{limit}}(\rho_{j_{limit}}) + \frac{p_r\rho_{past}^{r,ext}(f_{j_{limit}}^{Pext} - f_{j_{limit}}^{Pres})}{f_{j_{limit}}^{crop}} \tag{36}$$

### 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 4 and 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 6). These pastures yields are the quantity of grass grazed (as opposed to total grass grown) on a unit of land.

## 6 Example of model outputs

### 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 $p_{\chi}$. For each of these simulations, food consumption increases following a scenario inspired by the Millennium Ecosystem Assessment scenario "Global Orchestration" [Millennium Ecosystem Assessment Board, 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

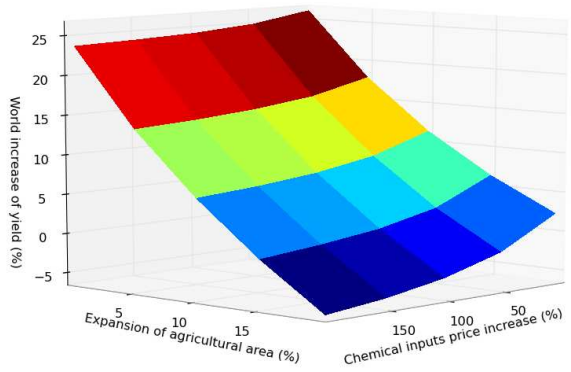



Figure 14: Variations of crop yields in function of chemical inputs price and expansion rate of agricultural lands 2001 and 2050.

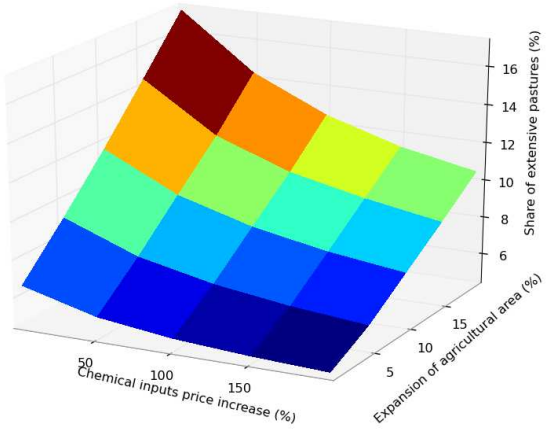



Figure 15: Variations of the proportion of extensive pastures in function of chemical inputs price and expansion rate of agricultural lands between 2001 and 2050.

simplicity. The maximal conversion speed of residual pastures is set to 20%. 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 15 and figure 14 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 $p_\chi$ 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 $p_\chi$ on the key drivers of the model, without particular regards to the realism of the envisaged evolutions.

### 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 $p_\chi$ disadvantages the use of chemical inputs over land and generate a yield reduction *ceteris paribus*. This effect stands out clearly in figure 14. Conversely, as arable land becomes scarcer, its shadow costs $\lambda$ 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 $p_\chi$, 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 $p_\chi$ is such that it brings out the non-linear form of the crop production function (see section 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 $p_\chi$ 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 15 shows that the proportion of extensive pastures diminishes as $p_\chi$ rises and as the deforestation rate drops. When $p_\chi$ 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 $p_\chi$. 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.

## 7 Discussion

The model presented in this paper 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 toward 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 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 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].

# 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 conjointly the effect of changes in food 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.

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| 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 |

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Table 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: 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 paper.

| | 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 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<br>Barley<br>Rye<br>Rye grass for forage and silage | wheat<br>barley<br>rye | wheat | 3.34 | 17.0 | 22.1 |
| Rice | rice | rice | 3.6 | 6.7 | 13.6 |
| Green corn (maize)<br>Maize<br>Maize for forage and silage | maize | maize | 3.56 | 9.2 | 21.8 |
| Millet<br>Sorghum<br>Sorghum for forage and silage | millet<br>sorghum | millet | 3.4 | 4.7 | 1.9 |
| Beans, dry<br>Beans, green<br>Broad beans, dry<br>Broad beans, green<br>Chick peas<br>Cow peas, dry<br>Lentils<br>Lupins<br>Peas, dry<br>Peas, green<br>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<br>peanuts | groundnuts | 5.67 | 1.3 | 1.6 |
| Rapeseed | rapeseed<br>canola | rapeseed | 4.94 | 1.5 | 1.6 |

Table 4: Monogastic feed conversion factor $\beta_m$ (Mkcal of feed / Mkcal of monogastric product). Share of food crops $\phi_m^{fc}$ and fodder $\phi_m^{fodder}$ 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 5.4

| Regions | $\beta_m$ | $\phi_m^{fc}$ | $\phi_m^{fodder}$ | $\beta_m \times \phi_m^{fc}$ | $\beta_{r,ext}$ | $\phi_{r,ext}^{grass}$ |
|---|---|---|---|---|---|---|
| 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 5: Feed conversion factor of intensive ruminants $\beta_{r,int}$ (Mkcal of feed / Mkcal of ruminant product). Share of food crops $\phi_{r,int}^{fc}$, fodder $\phi_{r,int}^{fodder}$ and grass $\phi_{r,int}^{grass}$ in feed. Calories of food crop needed to produce one calorie of intensive ruminant meat and milk $\beta_{r,int} \times \phi_{r,int}^{fc}$. From Bouwman et al. [2005] and modified as explained in section 5.4

| Regions | $\beta_{r,int}$ | $\phi_{r,int}^{fc}$ | $\phi_{r,int}^{fodder}$ | $\phi_{r,int}^{grass}$ | $\beta_{r,int} \times \phi_{r,int}^{fc}$ |
|---|---|---|---|---|---|
| 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 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 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 8: Calibrated calorie price $p_{cal}$ value in 2001 ($/Mkcal), calibrated initial slope of the production function $\alpha_{IC}$ in $/Mkcal and GTAP 2001 intermediate consumption $IC_{\chi}$ in billions of dollars

| Regions | $p_{cal}$ | $\alpha_{IC}$ | $IC_{\chi}$ |
|---|---|---|---|
| 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 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. |
| | $p_\chi$ | Index of fertiliser and pesticide price. |
| Data for calibration | $\rho^{actual}_j$ | Actual yield per land class (mean through the 1999-2003 period) in kcal/ha/yr. |
| | $IC_\chi$ | Consumption of the part of the agricultural sector modelled in LPJmL from the chemical and mineral sectors in 2001 in \$ (see section 5.2). |
| Calibrated parameters | $\omega^{fc}_{swo}$, $\omega^m_{swof}$, $\omega^r_{swof}$ | 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). |
| | $\alpha_{IC}$ | 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 9: Continued.

| | | |
|---|---|---|
| Biophysical parameters | $\rho_j^{max}$, $\rho_j^{min}$ | Potential yield and minimum (no inputs) yield ($\rho_j^{min} = 0.1 \times \rho_j^{max}$) in kcal/ha/yr. |
| | $\beta_m$, $\beta_{r,int}$, $\beta_{r,ext}$ | Feed conversion factor for monogastrics, intensive and extensive ruminants in 'kcal of feed'/'kcal of animal product'. |
| | $\phi_m^{fc}$, $\phi_m^{fodder}$, $\phi_{r,int}^{fc}$, $\phi_{r,int}^{fodder}$, $\phi_{r,int}^{grass}$, $\phi_{r,ext}^{grass}$ | 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) | $\rho_j$ | 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. |
| | $\lambda$ | 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. |