The challenge of meeting the future food needs.[*]

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Abstract

In the context of growing food needs and dietary change towards meat combined with a lack of arable lands, we explore to what extent shifting from traditional to cereal intensive livestock technologies appears as a land constraint relaxing mechanism. We develop a model designed to project agricultural land-uses based on fundamental supply/demand drivers. Analytical results reveal that the substitution of the intensive system for the extensive one relaxes the land constraint. Then, world food demand/supply and agricultural land-uses for the next decades are investigated and the contribution of the switch towards intensive systems in meeting the future food requirements is measured.

JEL Classification : Q11, Q15, Q18, Q24

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One of the main functions of land is to feed people. Growing at an unprecedented rate, the world's population reached 3 billion people in 1960 and concerns about the ability of land to feed people appeared, for some experts well founded. Forty years later, the world's population has doubled reaching 6 billion people, nevertheless, the recurrent specter of the Neo-Malthusian scenarios seems unwarranted. World food production has been kept in line with the growing food needs thanks to the noteworthy increase in agricultural yields. Between the early sixties and the late nineties, average world cereal yield has doubled from 1.4 to 3 tons per hectare while land in agricultural use[1] has only risen by 11% (FAO 2003). Despite these achievements, food shortage is still a challenge.

The world's population is predicted to rise to 7.5 billion by 2030 and to about 9 billion by 2050 and to stabilize during the second half of the century (United Nations Population Division 2004). Furthermore, the increase in the average world per capita income should induce a structural change in the human dietary habits towards more animal protein products (Bouwman 1997; Delgado *et al.* 1998; Yu *et al.* 2003; Keyzer *et al.* 2005).

The two following trends may cast some doubt on the ability of agricultural sector to fulfill growing food needs. First, no more or very little new land may be brought into agricultural use (Rosegrant *et al.* 2001; FAO 2003; Wiebe 2003). Agricultural lands may widen at the expense of forest, grassland or other natural habitat. Wiebe (2003) has established a database at the worldwide level which splits the global land surface into different land classes according to soil and climate characteristics. Land classes are ordered according to their suitability for agricultural production. Overlaiding this land quality map with a land-cover/use map (Loveland 2000) enables to analyze the land-cover/use with respect to land quality. Most of forests, grasslands and other natural habitats belong to land types which accumulate two disadvantages undermining their long term productive potential: their agricultural yields are low and they are highly fragile and vulnerable to land degradation (Wiebe 2003; van Kooten and Folmer 2004). The expansion of agricultural lands at the expense of marginal lands or forests cannot fit agricultural production in a sustainable way. Second, the ever-more intensive use of land in agricultural production through multiple cropping, excessive use of agrochemicals should continue to contribute to the slowdown in the growth rates of agricultural yields[2] (FAO 2003; UNEP 2002; Ruttan 2002; Rosegrant *et al.* 2001). Consequently, the productive capacity of the two "traditional" land constraint relaxing mechanisms (use of new arable lands and technical progress) seems to be threatened. Nevertheless, a more stringer fact appears: "in recent years, livestock production stemming from the intensive industrial livestock production system grew at more than six times the annual growth rate of the production based on grazing" (FAO 2003 p.166). The substitution of the highly productive intensive livestock production system for the grazing system, a large consumer of land, could relax the arable land constraint. The role played by this new land constraint relaxing mechanism is all the more important in regions where there is a shortage of land like in Asia (FAO 2003). This expected trend towards intensification of livestock industry should have major implications on future land uses, grazing lands being converted into cropland.

Several partial equilibrium models give detailed projections on the future world food demand, supply and trade (Alexandratos 1995; FAO 1998 and 2003; Rosegrant *et al.* 2001). Taking aside land constraints, they are unable to project agricultural land-uses related to food requirements. Another set of models has developed optimization problems in order to examine the relationship between the demand for land products such as agricultural and forest products and land-use. They deal with the agricultural sector together with the forestry sector (Stavins 1990 and 1999; Mac Carl 1996; Adams *et al.* 1998 and 1999). Stavins (1990 and 1999) analyze the economic forces which drive the optimal land allocation between agricultural and forest sectors, but without distinguishing the two livestock production systems. Forest and Agriculture Sectors Model (FASOM) built by Adams *et al.* distinguishes the two livestock production systems. Since the purpose of this study is to give an empirical basis to measure the role of agricultural and forest sectors in greenhouse gas emission/mitigation at the regional level (the United-States), its structure is too complex[3] for enlightening the economic forces which underpin the switch towards more intensive livestock production system. Examples of General Equilibrium Models that investigate the trade-offs between different land-use decisions are the Future Agricultural Model (FARM) of Darwin (1995) and a modified version of GTAP model

(Lee *et al.* 2005) that incorporates land-use decisions in agricultural and forest sectors. However, the model's structure does not permit to scrutinize more deeply the economic drivers of the switch towards more intensive livestock production system.

In this paper, we develop a model of agricultural land allocation linking the demands for food products with the one for land resources. Two broad categories of final food products are considered, namely, processed crop-and-meat and dairy products. Available agricultural area is divided into heterogeneous land classes according to soil and climate characteristics. Each land class may be wholly or partially brought into either crop cultivation, pastures or be lain fallow. The primary crop production may be either manufactured into processed crop products or transformed into feed and forage products: the main component of the animal diet within the intensive livestock production system. Pastures are used exclusively by the extensive grazing system. Thus, meat and dairy products may stem from two livestock production systems: either the intensive livestock production system or the extensive one.

First, we build a theoretical model based on the rent principle (Castle and Randall 1993) to understand how the rise in food requirements drives the switch towards the more intensive livestock production system, which leads to agricultural land-use changes. Second, the empirical version of the model designed at the global scale over the long run allows to project the optimal patterns of the use of different land resources. Furthermore, the model provides projections on food demands, food prices and opportunity costs of land. Besides, its ability to forecast the future world food picture, the model helps in measuring the contribution of the new land constraint relaxing mechanism in meeting future requirements by designing different analytical scenarios.

The paper is organized as follows. We present the model in section 2. The efficient allocation of land together with the optimal allocation are characterized in section 3. The empirical model as well as its results are presented in section 4. We conclude in section 5.

The Model

Since forestry and soil dynamics are excluded from the study, all the command variables of any period are only effective within that period. Hence for ease of notation, we omit time indexes.

Final consumption goods

We consider two aggregate consumption products, namely, meat and dairy products (or animal protein products) and processed crop products (or vegetarian products). We denote by x_a and x_v the respective consumption levels of meat and dairy products and processed crop goods. The instantaneous gross surplus, or utility measured in monetary units, generated by the instantaneous consumption of the consumption bundle $x = (x_a, x_v)$ for a level of food needs denoted by z ($z \geq 0$), is given by $U(x, z)$ (in brief U) where z is an exogenous parameter determining the need intensity. U is assumed to be additively separable and given by:

$$(1) \qquad U = U_a(x_a, z) + U_v(x_v, z) = \sum_l U_l(x_l, z) \quad \text{where} \quad l \in \{a,\, v\}$$

As functions of x_a and x_v, U_a and U_v are functions of class C^2, strictly increasing and strictly concave, satisfying the Inada conditions :

$$(2) \qquad \partial U_l/\partial x_l > 0 \quad \text{and} \quad \lim_{x_l \downarrow 0} \partial U_l/\partial x_l = +\infty \quad \text{and} \quad \partial^2 U_l/\partial x_l^2 < 0 \;\; l \in \{a,\, v\}$$

z is a positive parameter with respect to which U_a and U_v are both increasing. We assume also that the marginal surplus functions are both increasing with z. Thus:

$$(3) \qquad \partial U_l/\partial z > 0 \quad \text{and} \quad \partial^2 U_l/\partial x_l.\partial z > 0, \qquad \text{where} \quad l \in \{a,\, v\}$$

We denote by $U_l^{'}$, and sometimes by p_l, the partial derivative of U_l, that is $U_l^{'} = \partial U_l/\partial x_l = p_l$ and by $U_l^{''}$ the second derivative, that is $U_l^{''} = \partial^2 U_l/\partial x_l^2$, $l \in \{a,\, v\}$.

Land resources

The available land area is given and denoted by L. Since the land quality differs dramatically across geographical regions, we divide the surface L into different land classes. As pointed out by Wiebe (2003 p.6), *"Land quality refers to the ability of land to produce goods and services that are valued by humans. This ability derives from inherent/natural attributes of soils (e.g., hydrology and fertility), water, topography, vegetation as well as "produced" attributes such as infrastructure (e.g., irrigation and transportation) and proximity to population center."* Thus, two kinds of land quality, namely, inherent and managed land quality can be distinguished. In this work, land classes are established on the basis of the first definition (e.g., *inherent land quality*). Each land class is indexed by i with $i \in \boldsymbol{I} = \{1, ..., n\}$ and is characterized by: i) its agricultural yield with respect to each use, ii) its unitary production cost out of the cost of land, iii) its available area, denoted by L_i, with $\sum_{i=1}^{n} L_i = L$.

Food production

To produce processed crop products , there only exists one production system. Let us denote by r_{iv}, the processed crop yield[4] (e.g., the number of vegetarian products obtained per unit of land class i) and by q_{iv} the quantity of this good produced on land class i. Thus, $q_{iv}/r_{iv} = L_{iv}$ is nothing more than the surface allocated to crop production which is in turn transformed into vegetarian products. Then, c_{iv} is the unitary production cost, equal to the marginal production cost, of these products on land class i[5].

Meat and dairy products may stem from two livestock production systems. The first one is the extensive grazing production system which exploits land directly through grazing. The second one is the intensive system which uses land indirectly through consumption of fodder and feed grains obtained from primary crop production.

Extensive grazing production system. Let r_{ip} be the amount of meat and dairy goods produced per unit of land class i[6]. The total production of animal protein products based on grazing on land class i is denoted by q_{ip}. Thus, $q_{ip}/r_{ip} = L_{ip}$ is the area of land i allocated to pasture to obtain q_{ip} units of animal protein products. We denote by c_{ip} the unitary production cost, equal to the marginal cost, within the extensive grazing system on land class i[7].

Intensive livestock production system. Let r_{ic} be the quantity of meat and dairy products obtained per unit of land i via this livestock production system[8] and q_{ic} be the quantity of animal protein commodities produced from livestock fed with primary crops cultivated on land i. The area of land class i which has to be allocated to crop cultivation to obtain q_{ic} units of products is $q_{ic}/r_{ic} = L_{ic}$. We denote by c_{ic} the unitary production cost of these final food products on land i which is also equal to the marginal production cost[9].

Therefore, the total production of animal protein products on land class i, denoted by q_{ia}, is equal to $q_{ia} = q_{ip} + q_{ic}$.

Characteristics of the two livestock production systems. In line with the stylized facts, the intensive livestock production system enjoys higher physical yields than the extensive one. However, this physical advantage is not a free lunch since the intensive livestock production system is more costly than the extensive one. Whatever the land class, the two following inequalities are observed:

Assumption 1 : $r_{ic} > r_{ip}$ for any $i \in \mathbf{I}$.

Assumption 2 : $c_{ic} > c_{ip}$ for any $i \in \mathbf{I}$.

Insert Figure 1 **here**

Production frontiers.

Each land class is available in limited quantity, we can define the maximum amount of each food product that could be produced on each land class. Let us denote by $\underline{q}_{ia}(q_{iv}, L_i)$ and $\overline{q}_{ia}(q_{iv}, L_i)$ (in brief $\underline{q}_{ia}$ and $\overline{q}_{ia}$) the maximum amount of meat and dairy products that can be obtained on land class i using respectively the extensive and the intensive systems for a given q_{iv}. Functions $\underline{q}_{ia}$ and $\overline{q}_{ia}$ are characterized by the respective equations :

$$(4) \qquad \underline{q}_{ia}(q_{iv}, L_i) \equiv r_{ip}. \left[L_i - \frac{q_{iv}}{r_{iv}} \right], \quad q_{iv} \in [0, r_{iv}.L_i]$$

$$(5) \qquad \bar{q}_{ia}(q_{iv}, L_i) \equiv r_{ic}. \left[L_i - \frac{q_{iv}}{r_{iv}} \right], \quad q_{iv} \in [0, r_{iv}.L_i]$$

Symmetrically, we define $\underline{q}_{iv}(q_{ia}, L_i)$ and $\overline{q}_{iv}(q_{ia}, L_i)$ (in brief $\underline{q}_{iv}$ and $\overline{q}_{iv}$) as the maximum amount of processed crop products that can be produced on land class i for a given

q_{ia} and stemming respectively from the extensive and the intensive livestock systems. Functions $\underline{q}_{iv}$ and $\overline{q}_{iv}$ are defined by the two following equations:

$$\underline{q}_{iv}(q_{ia}, L_i) \equiv r_{iv}. \left[L_i - \frac{q_{ia}}{r_{ip}}\right], \quad q_{ia} \leq r_{ip}.L_i \tag{6}$$

$$\bar{q}_{iv}(q_{ia}, L_i) \equiv r_{iv}. \left[L_i - \frac{q_{ia}}{r_{ic}}\right], \quad q_{ia} \leq r_{ic}.L_i \tag{7}$$

The Social Planner Problem

The problem of the social planner is to maximize the sum of the discounted social net surplus under each land class constraint. However, as noted in the preceding section, at any time period, the command variables have effects only within the same period. Thus, the problem can be reduced to a sequence of static problems, one for each time period. Let (P) be the static problem having to be solved at any period:

$$(P) \quad \text{Max}_{x_a, x_v, q_{ic}, q_{ip}, q_{iv}} \quad \sum_l U_l(x_l, z) - \sum_{i=1}^n c_{ic}.q_{ic} - \sum_{i=1}^n c_{ip}.q_{ip} - \sum_{i=1}^n c_{iv}.q_{iv}$$

$$\begin{array}{llll} \text{s.t.} & \sum_{i=1}^n (q_{ic} + q_{ip}) - x_a \geq 0 & & (\mu_a) \\ & \sum_{i=1}^n q_{iv} - x_v \geq 0 & & (\mu_v) \\ & L_i - \frac{q_{ic}}{r_{ic}} - \frac{q_{ip}}{r_{ip}} - \frac{q_{iv}}{r_{iv}} \geq 0 & \text{for} \quad i \in \mathbf{I} & (\lambda_i) \\ & x_a \geq 0, \quad x_v \geq 0, & & (\gamma_a, \gamma_v) \\ & q_{ic} \geq 0, \ q_{ip} \geq 0, \ q_{iv} \geq 0 & \text{for} \quad i \in \mathbf{I} & (\gamma_{ic}, \gamma_{ip}, \gamma_{iv}) \end{array}$$

The multipliers μ_a and μ_v are respectively the implicit prices of meat and dairy products and the ones of processed crop products. λ_i is the implicit price of land class i or more commonly called the opportunity cost of land. An immediate implication of the Inada conditions is that both x_a and x_v are strictly positive so that the corresponding non-negativity constraints may be deleted.

Optimal allocations of land

The land constraint relaxing mechanism under study is reflected by the transfer of livestock production from the extensive to the intensive systems. The simplest way to show

how this mechanism works is to consider the optimal land allocation on land class i assuming that production levels on the other land classes are optimally determined and denoted by $\sum_{j \neq i} q_{jl}$ where $l \in \{a, v\}$.

Efficiency and substitutions within the same land class

Let us examine how land class i must be allocated for producing a feasible bundle $q_i = (q_{ia}, q_{iv})$ for a given q_{iv}. We denote by $q^e_{ic}(q_i, L_i)$ (in brief q^e_{ic}) and $q^e_{ip}(q_i, L_i)$ (in brief q^e_{ip}) the quantities of meat and dairy products having to be supplied by respectively the intensive and the extensive systems in order to minimize the cost of q_i, and by $L^e_{ic}(q_i, L_i)$ (in brief L^e_{ic}) and $L^e_{ip}(q_i, L_i)$ (in brief L^e_{ip}) the corresponding allocation of land.

If the production level of animal protein products (q_{ia}) is sufficiently low, meaning that $0 < q_{ia} < \underline{q}_{ia}$, then, the whole meat and dairy production can be met by using only the cheaper production channel (the extensive grazing system). $L^e_{ip} = q_{ia}/r_{ip}$ units of land are allocated to pastures, $L^e_{iv} = q_{iv}/r_{iv}$ units of land are devoted to crop for the production of vegetarian goods, finally, $L_i - L^e_{ip} - L^e_{iv} > 0$ units of land are lain fallow. Any marginal increase in any final consumption good can be met by extending the area devoted to its production, crop cultivation for processed crop products and pastures for animal protein products. Because land is in excess supply, the marginal cost of each final good is nothing more than its direct monetary marginal cost:

$$(8) \qquad MC_{ia} = c_{ip} \quad \text{and} \quad MC_{iv} = c_{iv} \;, \quad \forall \quad q_{ia}, q_{iv} \;:\; 0 < q_{ia} < \underline{q}_{ia}$$

Let us now consider larger meat and dairy production levels, $q_{ia} \in]\underline{q}_{ia}, \overline{q}_{ia}]$. Producing animal protein products through the intensive livestock production system implies that $L_i - \frac{q_{iv}}{r_{iv}} - \frac{q_{ia}}{r_{ic}}$ units of land are lain fallow. However, it is worth noting that the production cost of the bundle q_i may be reduced by exploiting the land set aside. To illustrate the point, let us suppose that the production of one unit of meat and dairy products is transferred from the intensive system to the extensive one [10]. From Assumption 2, we deduce that the total production cost is reduced by $(c_{ic} - c_{ip})$. Consequently, to minimize the production cost of the bundle q_i, the production stemming from the less costly system which is also the less productive has to be maximized: any piece of land lain fallow is a waste. The whole available land for meat and dairy production ($L_i - \frac{q_{iv}}{r_{iv}}$) has to be exploited. Thus, we must have:

$$r_{ic}L_{ic} + r_{ip}L_{ip} = q_{ia} \quad \text{and} \quad L_{ic} + L_{ip} = L_i - q_{iv}/r_{iv}. \tag{9}$$

Solving for L_{ic} and L_{ip}, we get:

$$L_{ic}^e = \frac{q_{ia} - r_{ip}\left[L_i - q_{iv}/r_{iv}\right]}{r_{ic} - r_{ip}} \quad \text{and} \quad L_{ip}^e = \frac{r_{ic}\left[L_i - q_{iv}/r_{iv}\right] - q_{ia}}{r_{ic} - r_{ip}} \tag{10}$$

hence:

$$q_{ic}^e = \frac{r_{ic}\left[q_{ia} - r_{ip}\left(L_i - q_{iv}/r_{iv}\right)\right]}{r_{ic} - r_{ip}} \quad \text{and} \quad q_{ip}^e = \frac{r_{ip}\left[r_{ic}\left(L_i - q_{iv}/r_{iv}\right) - q_{ia}\right]}{r_{ic} - r_{ip}} \tag{11}$$

Although land class i is wholly exploited, animal protein commodities production can be increased keeping contant the production of processed crop products thanks to the ability to switch towards more intensive agricultural practices. By differentiating equations (11) with respect to q_{ia}, meat and dairy products based on grazing system diminishes by $-\frac{\partial q_{ip}^e}{\partial q_{ia}} = r_{ip}/(r_{ic} - r_{ip})$ units whereas the one stemming from the intensive livestock production system expands by $\frac{\partial q_{ic}^e}{\partial q_{ia}} = r_{ic}/(r_{ic} - r_{ip})$ units. Consequently, pasture land are converted into cropland and the size of land transfer, obtained by differentiating (10), amounts to $\frac{\partial L_{ip}^e}{\partial q_{ia}} = \frac{1}{r_{ic} - r_{ip}} = -\frac{\partial L_{ic}^e}{\partial q_{ia}}$. Since the intensive livestock production system is more costly (*Assumption* 2), an additional cost per unit of grazing land converted into cropland is incurred amounting to $(c_{ic}.r_{ic} - r_{ip}.c_{ip})$. Consequently, *the full marginal production cost* of meat and dairy products is equal to (see figure 2):

$$MC_{ia} = \frac{c_{ic}.r_{ic} - c_{ip}.r_{ip}}{r_{ic} - r_{ip}} \equiv \overline{MC}_{ia} \;\; \forall \;\; q_{ia}, q_{iv} \; : \; \underline{q}_{ia} < q_{ia} < \overline{q}_{ia} \tag{12}$$

$$MC_{ia} = c_{ip} + \frac{r_{ic}(c_{ic} - c_{ip})}{(r_{ic} - r_{ip})} = c_{ic} + \frac{r_{ip}(c_{ic} - c_{ip})}{(r_{ic} - r_{ip})} \tag{13}$$

with $MC_{ia} > c_{ic}$.[11]

Thus, the cost increment generated by producing one more unit of meat and dairy products on land class i is equal to the sum of the direct marginal production cost (c_{ic} for the intensive livestock system and c_{ip} for the extensive grazing system) and the one induced by the changes in agricultural practices required to relax the land constraint ($\frac{r_{ip}(c_{ic}-c_{ip})}{(r_{ic}-r_{ip})}$ for the intensive livestock production system and $\frac{r_{ic}(c_{ic}-c_{ip})}{(r_{ic}-r_{ip})}$ for the extensive grazing system) (see appendix A).

The switch towards more intensive livestock production system also enables to sustain a marginal rise in the production of vegetarian products ($dq_{iv} > 0$) leaving the production of meat and dairy products unchanged. The required additional area having to be allocated to processed crop production amounts to dq_{iv}/r_{iv}, thus, land allocated to the production of animal protein products has to decrease since agricultural area is wholly cultivated. Nevertheless, the production of animal protein products may be kept constant by transferring the production of $-\frac{\partial q_{ip}^e}{\partial q_{iv}} = \frac{r_{ip}.r_{ic}}{(r_{ic}-r_{ip}).r_{iv}} = \frac{\partial q_{ic}^e}{\partial q_{iv}}$ (see equation 11) units of animal protein products from the extensive grazing system to the intensive one. As a result land allocated to pastures falls by $dL_{ip}^e = \frac{\partial q_{ip}^e}{\partial q_{iv}}.\frac{1}{r_{ip}} = \frac{r_{ic}}{(r_{ic}-r_{ip}).r_{iv}}$ units whereas land allocated to crop used as input within the intensive system rises by $dL_{ic}^e = \frac{\partial q_{ic}^e}{\partial q_{iv}}.\frac{1}{r_{ic}} = \frac{r_{ip}}{(r_{ic}-r_{ip}).r_{iv}}$ units. In this way, area allocated to meat and dairy production decreases by $1/r_{iv}$ units. Thus, *the full marginal production cost* of processed crop products may be split into two parts. The first one is the *direct marginal production* cost equal to c_{iv}. The second one is the cost induced by the land-use changes (or the switch in agricultural practices) which amounts to: $c_{ic}dq_{ic}^e + c_{ip}dq_{ip}^e = \frac{r_{ic}r_{ip}(c_{ic}-c_{ip})}{r_{iv}(r_{ic}-r_{ip})}.dq_{iv}$. Hence, *the full marginal production cost* of processed crop products is given by the following equation (see figure 2):

$$(14) \qquad MC_{iv} = c_{iv} + \frac{r_{ic}.r_{ip}(c_{ic}-c_{ip})}{r_{iv}(r_{ic}-r_{ip})} \equiv \overline{MC}_{iv} \;\; \forall \quad q_{ia}, q_{iv} \; : \; \underline{q}_{iv} < q_{iv} < \overline{q}_{iv}$$

where $\overline{MC}_{iv} > c_{iv}$.

Thus the marginal costs MC_{ia} and MC_{iv} are jumping upwards as illustrated in figure 2.

Insert Figure 2 here

The productive capacity of the new relaxing land constraint mechanism.

Having the marginal cost functions of each food product in hand, we characterize the optimal land allocation to the intensive livestock production, to the extensive one and to crop cultivation used to produce vegetarian commodities which are denoted respectively by L_{ic}^o, L_{ip}^o and L_{iv}^o and the optimal production bundle $q_i^o = (q_{ia}^o, q_{iv}^o)$ on land class i. According to the level of food needs, several cases may arise. Nevertheless, only one specific case[12] is useful to consider that is the one in which both food commodities are produced on land class i and meat and dairy products stem from a mix between the two livestock production systems (see figures 3). This case is described in details in Appendix B. To examine the productive capacity of the new land constraint relaxing mechanism, we do comparative static with respect to the level of food need intensity (z).

Following a marginal increase in the food need intensity (dz), marginal surplus curves of each food products move rightwards (see figures 3). This contributes to a marginal increase in the optimal production level of each food products which may be characterized by deriving condition (A-2, see appendix A) with respect to z. Thus, $\frac{\partial q_{ia}^o}{\partial z}$ and $\frac{\partial q_{iv}^o}{\partial z}$ are given by:

$$\frac{\partial q_{ia}^o}{\partial z} = -\frac{\partial^2 U_a/\partial x_a.\partial z}{U_a''} \quad \text{and} \quad \frac{\partial q_{iv}^o}{\partial z} = -\frac{\partial^2 U_v/\partial x_v.\partial z}{U_v''} \tag{15}$$

Insert Figures 3 here

Since any optimal production function is also efficient[13], the changes in agricultural practices may be determined from equations (11). Production of animal protein products stemming from the intensive livestock production system (q_{ic}^o) is driven up,

$$\begin{aligned} \frac{\partial q_{ic}^o}{\partial z} &= \frac{\partial q_{ic}^e}{\partial q_{ia}}.\frac{\partial q_{ia}^o}{\partial z} + \frac{\partial q_{ic}^e}{\partial q_{iv}}.\frac{\partial q_{iv}^o}{\partial z} \\ &= +\frac{1}{r_{ic}-r_{ip}}\left[r_{ic}.\frac{\partial^2 U_a/\partial x_a\partial z}{U_a''} + \frac{r_{ic}.r_{ip}}{r_{iv}}.\frac{\partial^2 U_v/\partial x_v\partial z}{U_v''}\right] > 0 \end{aligned} \tag{16}$$

whereas the one coming from the less productive livestock production (q_{ip}^o) is expected to fall by :

$$\begin{aligned} \frac{\partial q_{ip}^o}{\partial z} &= \frac{\partial q_{ip}^e}{\partial q_{ia}}.\frac{\partial q_{ia}^o}{\partial z} + \frac{\partial q_{ip}^e}{\partial q_{iv}}.\frac{\partial q_{iv}^o}{\partial z} \\ &= -\frac{1}{r_{ic}-r_{ip}}\left[r_{ip}.\frac{\partial^2 U_a/\partial x_a\partial z}{U_a''} + \frac{r_{ic}.r_{ip}}{r_{iv}}.\frac{\partial^2 U_v/\partial x_v\partial z}{U_v''}\right] < 0 \end{aligned} \tag{17}$$

Summing up the two previous equations, we can verify that $\frac{\partial q^o_{ic}}{\partial z} + \frac{\partial q^o_{ip}}{\partial z} = \frac{\partial^2 U_a/\partial x_a.\partial z}{U''_a} = \frac{\partial q^o_{ia}}{\partial z}$. The switch towards the more intensive livestock production system permits not only to fuel the production of animal protein products but also to transfer $dL^o_{ic} + dL^o_{ip} = \frac{\partial q^o_{ic}}{\partial z}.\frac{1}{r_{ic}} + \frac{\partial q^o_{ip}}{\partial z}.\frac{1}{r_{ip}} = \frac{1}{r_{1v}}.\frac{\partial^2 U_v/\partial x_v.\partial z}{U''_v} > 0$ units of land from the production of animal protein products to the one of vegetarian products. Bringing them into crop cultivation, the production of processed crop products rises by $\frac{\partial^2 U_v/\partial x_v.\partial z}{U''_v}$ units. Since any marginal increase in the food needs may be met by rising production of both food products whereas the area available for agricultural production is wholly exploited, the substitution between the two livestock production systems may be considered as *a reserve of productivity.*

According to figure 3, land class i's rent is kept constant and still equal to $\lambda^o_i = \frac{r_{ic}.r_{ip}.(c_{ic}-c_{ip})}{(r_{ic}-r_{ip})}$. Let us now shed more light on the economic meaning of this result. Thanks to the ability to produce animal protein products from two systems (one being more intensive in land), any marginal rise in food requirements may be met by switching towards more intensive livestock feeding technologies. The weight of the production coming from this system in the total production of protein products is established in order to satisfy: i) not only the increase in the production of meat and dairy products induced by a marginal food requirements-rise, ii) but also the demand for cropland required to satisfy the rise in the production of vegetarian products induced by a marginal change in the food requirements. Even if agricultural area is totally exploited no more pressure is exerted on land resources. Consequently, land rents being constant, this substitution may be seen also as *a safety valve* in the meeting of future food needs.

If animal protein products are produced from a mix between the two livestock production systems on land class i, every marginal increase in food needs is fulfilled by moving towards the more intensive livestock system on land class i. Optimal land allocation and production levels on the other land classes are not affected as well as the other land classes opportunity costs and food prices. The same type of results may be observed if meat and dairy products stem exclusively from the extensive livestock production system and if some piece of land class i is lain fallow (see case 1, Appendix A). In this case, any marginal increase in food needs is satisfied by bringing into use some piece of land lain fallow. Optimal land allocation, production levels on the other land classes, land opportunity costs and food prices are kept constant. Land lain fallow appears as the reserve of productivity and a safety valve. However, the optimal production levels, land allocation, land opportunity costs and food prices are expected to change following a marginal increase in food needs if land class i is wholly cultivated and if animal protein products stem from either the extensive grazing system or the intensive one[14] (see cases 2 and 4, Appendix A).

The Empirical Model

The model is designed at the worldwide level[15] and over the long term[16]. It is calibrated in time steps of ten years and 1990/99 is the base decade[17].

Data

Demand function for each food product[18] takes the following form:

$$D_l = B_l.P_l^{\alpha_l}.y^{\beta_l}.N, \quad l \in \{\text{a, v}\} \tag{18}$$

where D_l, the world demand for good l is expressed in billion of tons, B_l is a good-specific constant parameter[19], P_l is the price of the food product l in dollars per ton, y is the world average per capita income expressed in dollars, N is the world population in billion of people, α_l and β_l are respectively the price and the income elasticities.

Figures 4 depict the respective patterns of the world population and the world average per capita income for the next decades. It is worth noting that the rise in the food requirements should be substantial until the middle of this century and should stabilize over the next five decades[20]. The initial levels of income and price elasticities for both food products are reported in table 1. The income elasticities are established in order to reproduce the change in the dietary habits towards more meat and dairy products (Delgado *et al.* 1998; Yu *et al.* 2003; Golub *et al.* 2007).

In order to take into account the heterogeneity of agricultural land at the worldwide level, we exploit an USDA's database which splits the world surface into nine land classes on the basis of soil resources and climate (Wiebe 2003). Land classes (or productivity classes) are classified according to the severity of the constraints they impose on sustainable rainfed agricultural production. Land classes VII, VIII and IX are set aside from the study because of too numerous biophysical constraints (see appendix B). Figure 5 and table 2 depict the spatial distribution of the different land classes. Over the reference decade, agricultural area occupied 4.7 billion of hectares, it may widen at the expense of either natural habitats, savannahs, shrublands or forests. Nevertheless, taking into account land suitability for agricultural production, very few new arable lands are available at the worldwide level (FAO 2003; Wiebe 2003; van Kooten and Folmer 2004). Overlaiding the land quality (Wiebe 2003) with a land use/cover map (Loveland 2000) reveals that about 30% of world forests are unsuitable for agriculture and 50% of them belong to land classes which have low agricultural yields and once they are deforested, they are much more vulnerable to land degradation (van Kooten and Folmer 2004) as a result of which they can not fit agricultural production in a sustainable way. Consequently, agricultural area is supposed to be constant along the simulation period.

We break the agricultural yields (the number of final food products obtained per unit of land) into primary yields and coefficients of transformation of primary products into food products[21]. Similarly, we distinguish the primary production costs[22] and the costs of transformation of primary products into final food products. Whereas the primary yields and costs are specific to each land class, the coefficients and the costs of transformation do not depend upon the land class on which the land outputs are produced. USDA's database provides information about neither the primary yields nor the primary production costs assigned to each land class. However, exhaustive information are given at the country level for primary crop yields by FAOSTAT and for intensive and extensive livestock systems yields by Bouwman[23](1997). Thus, having, on the one hand, information about the spatial distribution of land quality (see figure 5), and on the other hand, referenced spatial data about primary crops and intensive and extensive livestock systems yields, average primary yields are assigned to each land class. Primary production costs with respect to each land class are designed in the same way. Referenced data about primary production costs defined out of the cost of land are extracted from GTAP $5-4$. The coefficients of transformation of land outputs into final food products are extracted from FAOSTAT, the costs of transformation are provided by GTAP $5-4$. In this study, technical progress enhances land quality in the sense that agricultural yields are steadily increasing and production costs are diminishing (see appendix B). Table 3 depicts the agricultural yields assigned to each land class at different dates (2000, 2050 and 2100).

Insert Figures 4, 5 about here

Insert Tables 1, 2, 3 about here

Productive capacity of the switch towards the more intensive livestock production system. In the context of a slow down in agricultural productivity combined with a lack of new arable lands, we aim at measuring in what extent the substitution between the two livestock production systems may help in meeting increasing world food requirements.

Let us first draw a picture of the world agricultural sector over the first decade (2000/09). The whole available land is brought into agricultural use. The most fertile land classes are intensively cultivated being allocated for crops. Land classes I and II are exclusively cultivated for crops, land class III is simultaneously allocated to crops and to grazing and land classes IV, V and VI are allocated to pasture land. Consequently, the world agricultural production is highly concentrated. About 94% of the world food production comes from the classes I, II and III whereas they occupy one third of the total agricultural available area (see table 2 and figure 8). The world agricultural sector facing the rise in food requirements is expected to use more and more intensively agricultural land (see figures 4). Two kinds of intensification may be distinguished. On the one side, the enhancement of land productivity driven by the adoption of new technologies or the cultivation of new and high-yielding crop varieties may relax the land constraint. On the other side, the world agricultural sector may benefit from a productivity-reserve substituting the intensive livestock system for the extensive one since around 62% of the animal protein commodities production stems from the more productive livestock system in 2000/09 and 75% of the world agricultural area is allocated to pasture land.

In order to measure the power of these two land constraint relaxing mechanisms. Three scenarios are built:

1. In the first scenario named *Land-Use Change* (in brief LUC)[24], land quality is left constant over the next decades in other words the rate of technical progress is nil.

Thus, the only way to satisfy the increasing food needs is to switch towards the intensive livestock production system, pasture lands are converted into cropland.

2. In the second one named *No Substitution* (in brief NS), agricultural land allocation i) to crops which are next transformed into vegetarian products, ii) to the intensive livestock production system and iii) to the extensive system is the same as the one projected for the first decade over the simulation period. Consequently, no substitution between the two livestock production systems can occur. The rise in the agricultural production can only come from the enhancement of land quality.

3. In the third one, called *Land Quality* (in brief LQ), we use a rough "best guess" estimate of the future growth rates of technical progress and land-use decisions are endogenous.

First, we analyze deeply the results of each scenario in order to scrutinize the working of each land constraint relaxing mechanism, then, we compare the results of the different scenarios in order to measure the role played by each mechanism.

Insert Figures 6, 7, 8 about here

Insert Table 4, 5, 6 about here

Land-use changes scenario. Keeping the land quality constant, the agricultural yields as well as the production costs are left unchanged. Formally, the intervals within which each step of the marginal functions are the pertinent ones but also the values of the functions within the intervals are the same over the simulation period. However, boosted by the food needs intensity-increase, the marginal surplus functions shifts rightwards. Every future rise in food requirements may only be satisfied thanks to the switch towards more intensive livestock system. To analyze the effects of these changes upon the key variables, we divide the simulation period into two sub-periods.

Over the first sub-period which begins in 2010/09 and ends in 2030/39, global consumption of both food products is steadily increasing[25]. The share of meat and dairy production stemming from the more productive livestock production system is rising from around 66% in 2010/09 to 100% in 2030/39, which leads to substantial land-use changes.

At the beginning of the simulation period, 75% of the agricultural area is allocated to grazing lands. Over the next tree decades, they are gradually converted into cropland to disappear by 2030/39 (see table 5). The productive capacity of the substitution between the two livestock production systems as well as its ability to slow down the rise in the land rents depends upon the quality of pasture land converted into cropland. By 2010/19, land class IV is allocated simultaneously to pastures and to crop cultivation. These land-use changes induce slight rises in land rents of land classes previously cultivated for crops that is land classes I, II and III (see table 5). Per capita consumption of both food products rise by 8% (see figures 6) and the rise in the food prices is moderate (see table 4). These results corroborate the idea that the changes in agricultural practices relaxes the land constraint. However, this optimistic view is mitigated when the switch occurs on very low-productive land classes. Until 2020/29, land class VI is exclusively exploited by the extensive grazing system, by 2030/39, it is allocated simultaneously to crop cultivation and to pasture land, leading to a slightly increase in per capita consumption of both food products and a noteworthy rise in land rents of the highest fertile-croplands. Land rents of land classes I, II, III, IV and V are around 1, 5 times[26] higher in 2030/39 than in 2020/29. Per capita consumption of both food products is projected to only rise by 3%[27] (see figures 6) and the increase in food prices is substantial (see table 4).

From 2040 onwards, the world agricultural production is not still able to be kept in line with the growing food needs. The total agricultural production is left constant meanwhile the land rents of all land classes climb up (see table 5). Per capita consumption of animal protein products rises slightly at the expense of the one of vegetarian products. Both food prices increase (see table 4). However, it worth noting that these rises will be lesser by 2050 with the slow down in the food needs intensity-increase (see figures 4).

No substitution scenario. Since the land allocation to different uses is fixed throughout the simulation period, the expected rise in food requirements may only be met thanks to the improvement in land quality. However, it is important to keep in mind that the growth rates of the technical progress are steadily decreasing (see table 3). To analyze the results of this scenario, the simulation period is divided into two sub-periods.

Over the first sub-period which ends in 2030/39, although global demands for both food products are projected to be steadily rising, per capita consumption of both food commodities are expected to be decreasing (see figures 6). This result reveals that the rise in the agricultural yields is not sufficient to satisfy the future food requirements. As a result the land rents as well as food prices climb up, indeed, the average decennial growth rate of food prices exceed 80% (see table 4). Nevertheless, let us notice the following points. Firstly, the rate of decrease of per capita food consumption is lower and lower (see figures 6). Secondly, the growth rates of the food prices are falling throughout the sub-period (see table 4). This two trends are explained by the slow down in the rise of food needs intensity (see figures 4).

Over the second sub-period (from 2040/49 to the end of the simulation period), global and per capita consumption of both food products are expected to rise (see figures 6). Vegetarian products prices are steadily decreasing and the rise in animal protein commodities prices is very slight and they decrease over the last decades (see table 4). Over this sub-period, the rise in food requirements is lower than over the previous one, thus, the enhancement of land quality enables to sustain increasing per capita consumption of both food products although the rise in the animal protein products prices is not avoided.

Land quality scenario. Since the available land is wholly cultivated by the first decade, to satisfy the growing food needs, the agricultural sector may i) rely on the exogenous improvements of land quality ii) or move towards the more intensive and the more expensive livestock production system.

Global demands for food products double over the next five decades, they increase only by 18% over the next five decades. Since the human diet is expected to change towards more animal products, the bulk of increase is forecast to come from these food commodities. For the next five decades, the global demand for meat and dairy products is expected to be multiplied by 2.2 whereas the demand for processed crop products are forecast to be 1.8 times higher in 2050 than current values. From 2050 to 2100, the global demand for meat and dairy products (respectively for processed crop products) rise by

32% (respectively by 11%). To sustain the rise in the world agricultural production, the share of meat and dairy products stemming from the intensive livestock production system is expected to be steadily increasing. Over the second decade, two-thirds of the meat and dairy production stems from the intensive livestock production system, this share enlarges to reach nearly 80% in 2050/59. Then, it is quite stable over the last five decades. It is worth noting that more substantial is the rise in the food requirements, higher is the rise in total agricultural production stemming from the substitution towards more intensive livestock production system. 65% of the agricultural production-development comes from this substitution in 2010/19 and this share lessens slightly until 59% in 2050/59. By 2060/69 to onwards, a larger share of the agricultural production stems from the land improvement quality[28]. The changes in agricultural practices leads to substantial agricultural land re-allocation. Over the first decade, around 75% of the world agricultural area is occupied by grazing lands. By 2030, the cropland is the dominant use since it covers 55% of the agricultural area (see figure 7). Moreover, it may be noticed that an ever-increasing share of the primary agricultural production is expected to come from the lowest-fertile land classes (see figure 8). Over the first decade, around 80% of the world's agricultural production come from land classes I and II which occupy less than 20% of the world agricultural area. Then, over the decade 2050/59, these two land classes supply around 55% of the world production.

Let us examine more deeply the land-use changes induced by the switch in agricultural practices. From 2000/09 to 2010/19, the food need intensity-rise is met thanks to the substitution of the intensive livestock system for the extensive one on land class III (see table 6). This change in agricultural practices together with the technical progress contribute to a quite substantial rise in per capita consumption of both food products (see figures 6) and a slight slow down in the land rents (see table 6), the land constraint is relaxing. The same trend is observed from 2030/39 to the end of the simulation period when grazing lands are gradually converted into cropland on land class V[29] (see table 6). Furthermore, it is worth noting that as lower fertile-grazing lands are converted into cropland the rise in the per consumption of both food products is slowed down and the land rents of higher fertile-croplands are driven up (see table 6). Consequently, in this case, the decrease in food prices is less important than over the previous periods (see table 4). In 2020/29, land class IV which was previously exclusively exploited by the extensive grazing system is allocated to crop and to pasture (see table 6), consequently, land rents of land classes I, II and III rise by around 8%.

Despite the rise in food needs, prices for processed crop products (respectively meat and dairy products) decrease by 27% (respectively by 20%) over the next five decades thanks to the combined effects of the changes in livestock feeding technologies and the enhancement of land productivity. Nevertheless, these rates are lower than the ones observed over the last four decades. From the early sixties to the late nineties, food prices decreased by around 40% in real terms (Wood *et al.* 2000; FAO 2005). This difference leads us to predict that land resources should be scarcer over the next decades than over the previous ones.

Comparison of the results of the different scenarios. Two elements permit to measure the power of a land constraint relaxing mechanism. The first one is the increase in food production/consumption induces by its use. The second one is the variation in food prices. In order to measure the role played by each mechanism in meeting the future food requirements, we compare the values of these variables in scenarios LUC and NS with the ones in the scenario LQ. We divide the simulation period into two sub-periods, the first one begins in 2000/09 and ends in 2030/39 and the second one begins in 2040/49.

Over the first decades (from 2000/09 to 2030/39), by analyzing figures 4, we see immediately that the increase in food requirements is projected to be substantial, indeed, by 2040/49, the growth rates of the world's population and, in a lesser extent, the ones of the average world per capita income are expected to slow down. Figures 6 reveal that the per capita consumption of both food products in the scenarios LUC and LQ are quite similar as well as their growth rates. But, the rise in the world food production induced by technical progress is not able to fulfill the rise in food requirements since per capita consumption of both food products are expected to decrease along this sub-period (scenario NS). Furthermore, the increase in food prices is curbed in the scenario LUC whereas in the scenario NS, the food prices are fueled. Thus, the analysis of the results of this sub-period corroborates the idea that the switch towards more intensive livestock production system is not only a reserve of productivity but also a safety valve.

Over the following decades, the food need intensity-rise becomes less and less substantial (see figures 4). In the scenario LUC, no land constraint relaxing mechanism is available, thus, world agricultural production is left constant. Therefore, we only compare the results of scenarios NS and LQ. The discrepancy between the growth rates of the per capita consumption of both food products across these scenarios is less and less important. However, the level of per capita consumption of both food products in scenario NS is much more lower than in the scenario LQ since world agricultural production is not able to be kept in line with the growing food needs along the first period by using only technical progress. Table 4 shows that the growth rates of the food prices in the scenarios NS and LQ are quite similar. This analysis reveals that the substitution between the two livestock production systems is not a necessary condition to fulfill to the food requirements when they are lower and lower. Whereas the improvement in agricultural land productivity was the main agronomic factor which underpinned the rise in world food production over the last four decades (FAO 2003), the results of this work reveals that an ever-increasing share of the future rise in world food production will be expected to come from the switch towards more intensive livestock production system over the next decades.

Concluding remarks

Over the next decades, the agricultural sector is facing the following dilemma: it should be able to satisfy growing food requirements whereas no more or very little new lands may be brought into cultivation and the growth rates of agricultural yields are projected to continue to decrease. However, switching towards more intensive livestock technologies is expected to relax the land constraint. A theoretical analysis of the model of agricultural land allocation reveals that this shift appears as i) not only a reserve of productivity since it enables to satisfy the rise in food requirements ii) but also a safety valve since it slows down the increase in the land rents and in food prices. Then, from an empirical framework, the role played by the substitution between the two livestock production systems has been measured at the world-wide level by building three analytical scenarios.

Since land resources are at the core of many environmental issues (biological carbon sequestration, preservation of biodiversity, land degradation), a global model of land-use defined in the long run may be considered as a necessary condition in order to study environmental issues related to land-use and land-use changes. In this work, we have developed a model where land is exclusively exploited to produce agricultural commodities. It may also be topical to examine the environmental changes driven by the agricultural sector. According to Tilman *et al.* (2001), *these changes may rival climate change in environmental and societal impacts.* The doubling of food production during the past 35 years was accompanied by large increases in global nitrogen, phosphorus fertilization and irrigation. Due to an excessive or inappropriate use of these production factors, about 30% of the world agricultural area currently suffers from soil degradation. The extent and the severity of this phenomena is more pronounced in developing tropical countries. To provide a better understanding of this environmental issue: *land degradation*, it should be relevant to link the level of food needs with the dynamics of agricultural yields as well as with one of the total arable land. Including a global timber market, the model should provide a better understanding of the land competition between the agricultural and the forest sectors (Hubert 2007.*a*). Besides forming a basis for forestry and agricultural production, land aids in the preservation of terrestrial biodiversity, carbon storage and recycling. Linking this model with a global timber market models and adding a carbon sequestration model, we should be able to explore the potential role of forests in greenhouse gas mitigation (Hubert 2007.*a* and 2007.*b*). Hertel *et al.* (2006) and Golub *et al.* (2007) have developed a Computable General Equilibrium model which is an extension of the GTAP model (Lee *et al.* 2005) *"that predicts patterns of land-use change at the global scale over the long run to enhance our understanding of land-use related greenhouse gas emissions"*. Since forestry plays an important role in land-uses and land-use changes, the comparative advantage of building our partial equilibrium model of agricultural land competition is that it is possible to link this model with a forward-looking model of the forest sector.

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Notes

[1]According to FAOSTAT's definition, land in agricultural use is the land used for temporary and permanent crops. In the present study, we will consider as agricultural land the area used for crop cultivation and pastures.

[2]Since the early eighties, a slowdown is observed in the growth rates of the crop yields (Rosegrant *et al.* 2001).

[3]Different land classes are distinguished, different food and forest commodities are supplied.

[4]This yield includes two elements. The first one is the primary crop yield (e.g., the quantity of primary crops obtained per unit of land), the second one is the coefficient of transformation of the primary crops into final food products.

[5]This cost includes not only the primary production cost absent from the cost of land but also the transformation cost of primary crop into final food products.

[6]This yield captures the pastures yield (the number of livestock per unit of land) and the coefficient of transformation of livestock products into meat and dairy products.

[7]It embraces both the unitary production cost of livestock out of the cost of land and the cost of transformation of livestock products into final consumption good.

[8]This yield includes different components. The first one is the primary crop yield. The second one is the coefficient of transformation of primary crop into fodder and feed grains. The third one is the feed ratio which determines the number of livestock products obtained per unit of feed and fodder grains (for an exhaustive definition of the feed ratio, see Bouwman 1997). The last component is the coefficient of transformation of livestock products into final food products.

[9]This cost includes the costs supported at each step of the production process. It does not take into account the opportunity cost of land.

[10] $(\frac{1}{r_{ip}} - \frac{1}{r_{ic}})$ units of land lain fallow are converted into pasture land.

[11] Easy calculations show that :

$$\frac{c_{ic}.r_{ic} - c_{ip}.r_{ip}}{r_{ic} - r_{ip}} > c_{ic} \Leftrightarrow (c_{ic} - c_{ip}).r_{ip} > 0$$

[12] The other cases are described in Appendix B.

[13] Tus,

$$q_{ic}^o = q_{ic}^e(q_i^o, L_i) \text{ and } q_{ip}^o = q_{ip}^e(q_i^o, L_i)$$

where $q_i^o = (q_{ia}^o, q_{iv}^o)$ and $q_{ia}^o = q_{ip}^o + q_{ic}^o$.

[14] This result does not hold if one of the other land classes is allocated to the two livestock production systems.

[15] The model is programmed with GAMS and solved with MINOS solver.

[16] The simulations are done over the next century since world food requirements are expected to be high due to the demand of the fast-growing developing countries.

[17] To calibrate the model, we have used the average values of each parameter over the nineties.

[18] Final food products derived from the cultivation of land under crops belong to the set : "processed crop products", it embraces all the vegetarian products derived from the cereal production as well as the one derived from oil-bearing, sugar crops and finally roots and tubers products. The set of "meat and dairy products" includes all meat like beef and veal, pig, poultry and sheep as well as all the products derived from animals like eggs, milk, butter, cream.

[19] This parameter is used to calibrate the demand function and to define the model in time steps of ten years (see appendix B and Chakravorty *et al.* 1997).

[20] The rise in food requirements is driven by the growth rates of the world's population and the ones of the per capita income.

[21]The primary agricultural yields times the coefficient of transformation is equal to the number of final food products obtained per unit of land.

[22]The primary production costs exclude the cost of land which is an endogenous variable.

[23]The pasture yields are nothing more than the number of livestock per unit of pasture land. Bouwman (1997) provides exhaustive information about the two livestock production systems at the worldwide level.

[24]Besides scrutinizing the effects of land-use changes in meeting the growing food needs, the analysis of this scenario helps to understand the impact of the increase in the food needs upon the key variables namely the food prices, the land allocation and the land rent. It illustrates the results of the analytical work.

[25]Global food consumption is projected to be multiplied by $1,6$ over this period.

[26]The rate of increase differs from one class to another, but not fundamentally.

[27]From figures 4, we notice that the rise in food needs is still important.

[28]The rise in the food needs is not sufficient to be supported by a change towards the more intensive and the more costly livestock production system.

[29]We have to keep in mind that over this period the growth in food needs is slowed down.

A Optimal allocations of land

Land rents when $p_a = \overline{MC}_{ia}$ *and* $p_v = \overline{MC}_{iv}$

A point which is worth being noticed and appears useful to characterize the optimal allocations, is that as far as the prices p_a and p_v of the consumption goods are either both equal to their lowest marginal cost or both equal to their highest marginal cost, then the rent is the same on each piece of land. This is trivial for $p_a = c_{ip}$ and $p_v = c_{iv}$ since in this case the rent is nil. Prices being equal to monetary average costs, nothing is left for the rent. But consider now the case in which $p_a = \overline{MC}_{ia}$ and $p_v = \overline{MC}_{iv}$, then the rents would be i)for the cropland producing the intermediate inputs of the intensive meat and dairy production system: $r_{ic}.\,[p_a - c_{ic}] = r_{ic}.\,\left[\overline{MC}_{ia} - c_{ic}\right]$ ii) for the pasture land: $r_{ip}.\,[p_a - c_{ip}] = r_{ip}.\,\left[\overline{MC}_{ia} - c_{ip}\right]$ iii) for the cropland producing the intermediate input of the processed crop final consumption good: $r_{iv}.\,[p_v - c_{iv}] = r_{iv}.\,\left[\overline{MC}_{iv} - c_{iv}\right]$.

Substituting for $\overline{MC}_{ia}$ and $\overline{MC}_{iv}$ in the above formulas, we obtain the same value of the land rent denoted by λ_i, that is :

(A-1)
$$\lambda_i = \frac{r_{ic}.r_{ip}.(c_{ic} - c_{ip})}{r_{ic} - r_{ip}}$$

Optimal land allocations among the two final food products

Case 1**:** For low needs, land of class i is abundant, meaning that at prices equal to direct marginal costs, $p_a = c_{ip}$ and $p_v = c_{iv}$, the demands can be supplied by using the less costly extensive livestock system. It is optimal provided that :

$$\begin{cases} r_{ip}\left\{U_a'(q_{ia} + \sum_{j\neq i} q_{ja},\, z) - c_{iap}\right\} = r_{iv}\left\{U_v'(q_{iv} + \sum_{j\neq i} q_{jv},\, z) - c_{iv}\right\} \\ L_i - \frac{q_{ia}}{r_{ip}} - \frac{q_{iv}}{r_{iv}} < 0 \end{cases}$$

Case 2**:** Let us now consider the case in which the need intensity is medium. Meat and dairy products and processed crop products are produced simultaneously on land class i, furthermore, meat and dairy products stem from a mix between the two livestock production systems. Such a case prevailing if and only if the following equalities are observed i) for meat and dairy products: $\overline{MC}_{ia} = U_a'(q_{ia}+, \sum_{j\neq i} q_{ja}\, z)$ thus $\bar{q}_{ia}(q_i^o,\, L_i) \geq q_{ia}^o \geq \underline{q}_{ia}(q_i^o,\, L_i)$ ii) for processed crop products: $\overline{MC}_{iv} = U_v'(q_{iv} + \sum_{j\neq i} q_{jv},\, z) > c_{iv}$ thus $\underline{q}_{iv}(q_{ia}^o, L_i) < q_{iv}^o < \bar{q}_{iv}(q_{ia}^o, L_i)$.

Optimal production choices q^o_{iv}, q^o_{ia} [30] are solution of the following system, noted S :

$$S \begin{cases} \lambda^o_i & = r_{ip}.\left(U'_a(q_{ia}+\sum_{j\neq i} q_{ja},\, z) - c_{ip}\right) = r_{ic}.\left(U'_a(q_{ia}+\sum_{j\neq i} q_{ja},\, z) - c_{ic}\right) \\ & = r_{iv}.\left(U'_v(q_{iv}+\sum_{j\neq i} q_{jv},\, z) - c_{iv}\right) \\ L_i & -\frac{q_{ip}}{r_{ip}} - \frac{q_{ic}}{r_{ic}} - \frac{q_{iv}}{r_{iv}} \geq 0 \end{cases}$$

where

$$\text{(A-2)} \qquad \begin{cases} U'_a(q_{ia}+\sum_{j\neq i} q_{ja},\, z) & = & \overline{MC}_{ia} \\ U'_v(q_{iv}+\sum_{j\neq i} q_{jv},\, z) & = & \overline{MC}_{iv} \end{cases}$$

Case 3**:** In this case, the levels of food needs are sufficiently high to exploit the whole available land class i but too low to produce meat and dairy products from a mix between the two livestock production systems. Such a case prevailing provided that i)for meat and dairy products: either $c_{ip} < U'_a(q_{ia}+\sum_{j\neq i} q_{ja}, z) < \overline{MC}_{ia}$ thus $q^o_{ia} = \underline{q}_{ia}(q^o_i,\, L_i)$ or $U'_a(q_{ia}+\sum_{j\neq i} q_{ja}, z) < c_{ip}$ thus $q^o_{ia} = 0$ ii) for processed crop products: either $c_{iv} < U'_v(q_{iv}+\sum_{j\neq i} q_{jv}, z) < \overline{MC}_{iv}$ thus $q^o_{iv} = \underline{q}_{iv}(q^o_i,\, L_i)$ or $U'_v(q_{iv}+\sum_{j\neq i} q_{jv}, z) < c_{iv}$ thus $q^o_{iv} = 0$.

Case 4**:** Lastly, the level of food needs may be such high that land class i is totally allocated to crop cultivation. Two cases may be distinguished. i) Land class i is totally devoted to the production of meat and dairy products: $U'_a(q_{ia}+\sum_{j\neq i} q_{ja}, z) > \overline{MC}_{ia}$ thus $q^o_{ia} = \bar{q}_{ia}(0, L_i)$ and $U'_v(q_{iv}+\sum_{j\neq i} q_{jv}, z) < c_{iv}$ thus $q^o_{iv} = 0$. ii) Both food commodities are produced on land class i: $U'_a(q_{ia}+\sum_{j\neq i} q_{ja}, , z) > \overline{MC}_{ia}$ thus $q^o_{ia} = \bar{q}_{ia}(q^o_{iv}, L_i)$ and $U'_v(q_{iv}+\sum_{j\neq i} q_{jv}, , z) > \overline{MC}_{iv}$ thus $q^o_{iv} = \bar{q}_{iv}(q^o_{ia}, L_i)$.

B The Empirical Model

The constant demand parameters and calibration of the demand functions. The constant demand parameters B_l are computed using the level of consumption and price of good l in the base decade (Chakravorty *et al.*, 1997). The average world consumption of food products and world food prices in the nineties are extracted respectively from FAOSTAT and OCDE-FAO (2006) together with World Bank (2006.a)[31] (table 1).

The inherent land classes. Land class I is characterized by highly fertile soils and long growing seasons. Classes with a shorter growing season due to higher or lower temperatures with soils of good quality are land classes II and III. Their minor limitations can be easily corrected and do not pose permanent restrictions. Productivity classes IV, V and VI face a range of biophysical constraints like short growing season due to high level of temperature, low nutrient status, low nutrient-holding capacity. These constraints may be mitigated by appropriate but costly technologies. Finally, the land classes VII, VIII and IX are unsuitable for agricultural production because of too numerous constraints. Consequently, they are set aside from the study.

Exogenous technical progress. Future growth rates of agricultural yields should be lower than those observed during the last four decades (Rosegrant 2001; Ruttan 2002). The annual growth rate of technical progress on agricultural yields is around 1.1% in 2000 and it is supposed to steadily decrease throughout the simulation period (Rosegrant *et al.* 2001). The rates of technical progress on primary production costs as well as on transformation costs are identical to the historical rates (FAOSTAT).

C Model validation

The model's reasonableness was tested by simulating the world agricultural model from 1960 to 2000. The simulations are done conditional on known exogenous changes in parameters along this period. The past growth rates of per capita income and the ones of global population were extracted from World Bank (World Bank 2006.*b*). The rates of increase of agricultural yields were defined from FAOSTAT. Since agricultural land had increased by 10% over this last four decades, we introduced an exogenous trend of new arable lands.

The model's performance over the historical period was judged by computing the absolute relative error, denoted by E_r and defined by the following equation:

(A-3) $$E_r = \left| \frac{P_t - A_t}{A_t} \right|$$

where P_t is the prediction for decade t and A_t is mean value of the observed variable over the decade t[32]. The world agricultural model built in this study enables to project many variables like global and per capita demands, food prices, agricultural land allocation, production of feed and forage products, crop production manufactured into final food products, the share of animal protein products stemming from each livestock production system. However, no data base informs about the share of each livestock production system in the production of animal protein products or about the consumption prices at the world-wide level along the period under study.

Table 7 shows the magnitude of error for some key variables along the validation period. The global demand for food products were over-estimated especially at the end of the simulation period. Nevertheless, the relative errors were lower than 10% except for the global demand for animal products over the decade 1990/99. Moreover, since the discrepancies between the observed and the predicted variables were becoming greater, we may think that the estimation of the income elasticities used were too high. The area allocated to cropland were systematically sub-estimated, nevertheless, the relative error was lower than 11% in absolute value. The area allocated to pasture land is slightly over-estimated. Finally, the model followed the general trend for food prices. Even if no exhaustive data was available at the world-wide level over the last decades for each food price, we know that food prices declined by 40% in real terms (Wood *et al.* 2000) and the model predicted that food prices decreased by 36% in real terms.

D Figure du modèle

E Tables

Figure 1: **Key variables in the agricultural sector**

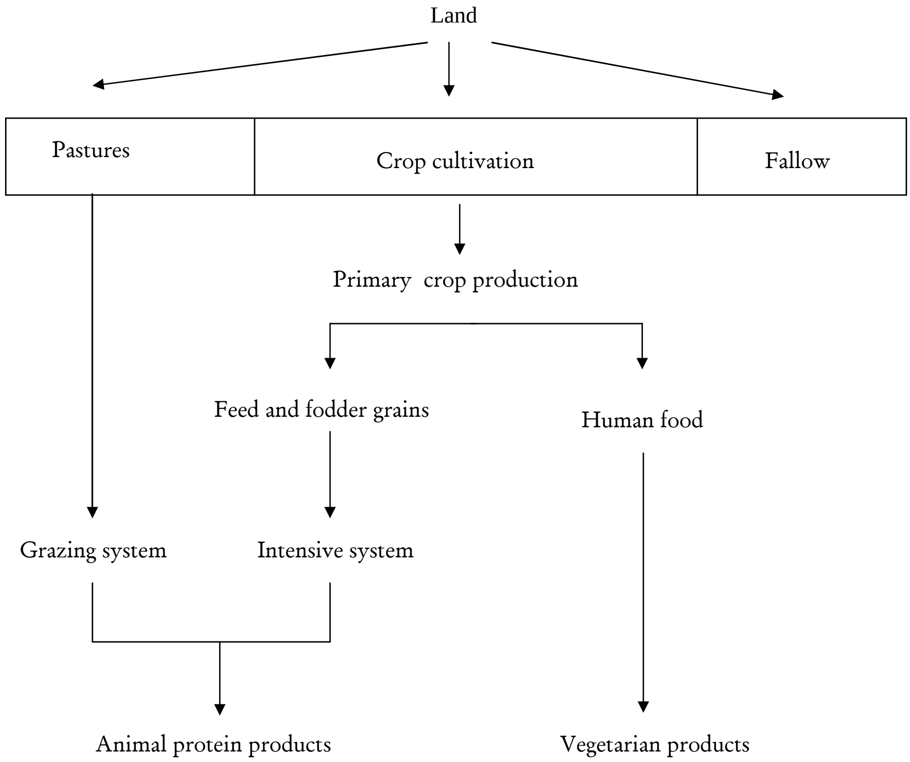
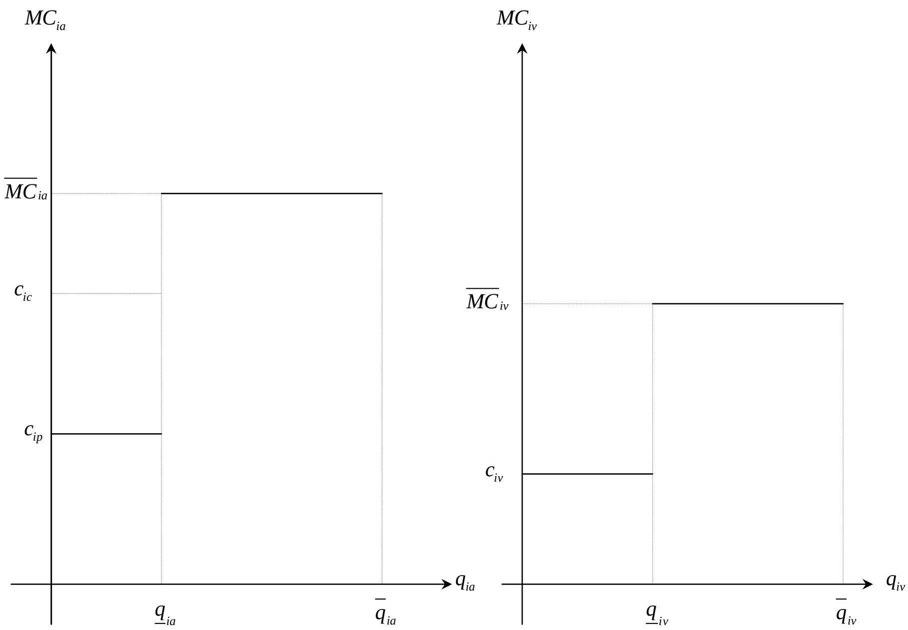


Figure 2: **Marginal production cost of each food product**



$$\overline{MC}_{ia} = c_{ip} + \frac{r_{ic}(c_{ic}-c_{ip})}{(r_{ic}-r_{ip})} = c_{ic} + \frac{r_{ip}(c_{ic}-c_{ip})}{(r_{ic}-r_{ip})}$$

$$\overline{MC}_{iv} = c_{iv} + \frac{r_{ic}.r_{ip}(c_{ic}-c_{ip})}{r_{iv}(r_{ic}-r_{ip})}$$

Figure 3: **Optimal allocation and effects on the optimal production levels on land class i of a marginal rise in food needs.**

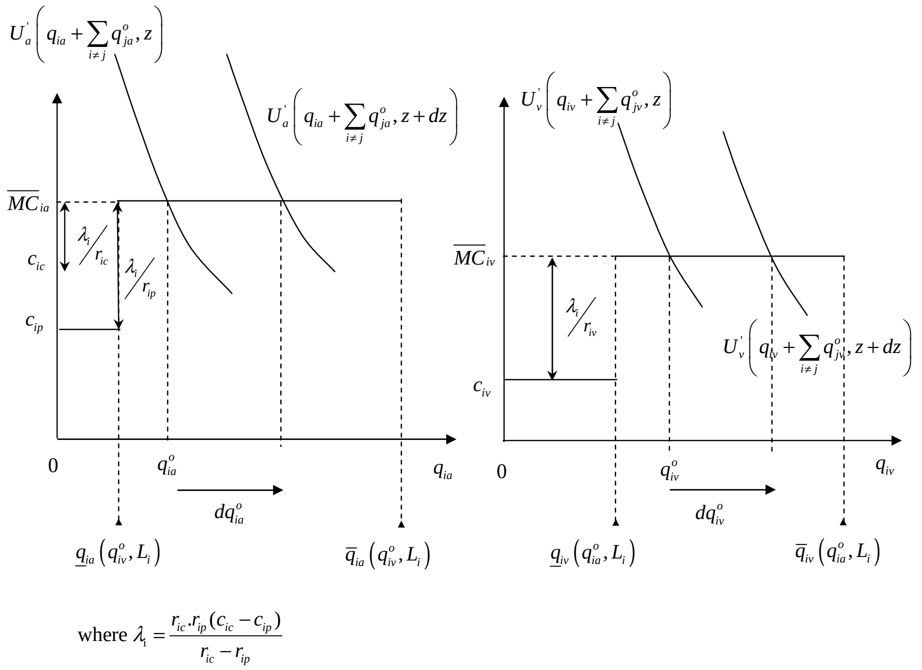
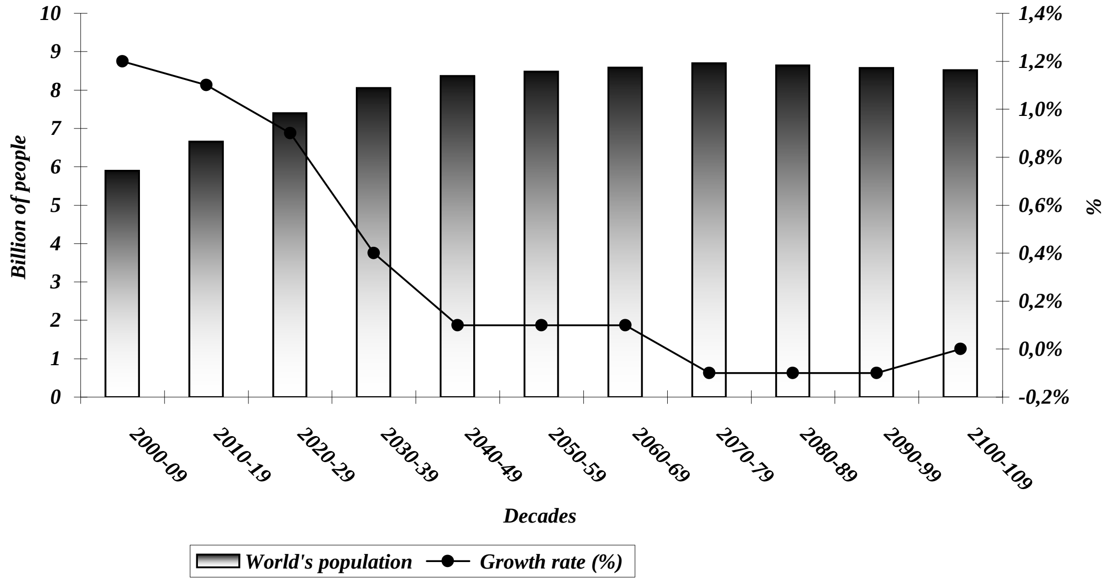


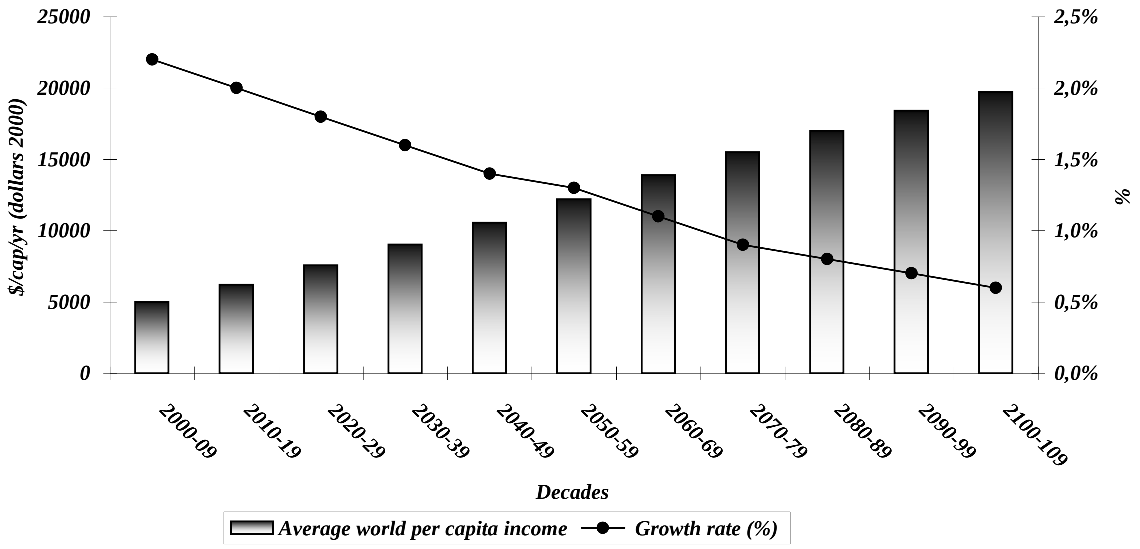
Table 1: **Values of the parameters used to calibrate the demand function.**

Average value on 1990-99	Meat and dairy products	Processed crop products
Annual per capita demand (t/cap)	0,15	0,58
Annual per capita income ($/cap)*	4905	4905
Population (Billion)	5,9	5,9
World Price ($/ton)	270	5000
Price-elasticity	-0,2	-0,17
Income-elasticity	0,6	0,35
Constant parameter	0,004971681	0,060636626

Figure 4: World population and average world per capita income from 2000 to 2100 and their growth rates



Source : UNDP 2004



Source : Madisson 2001

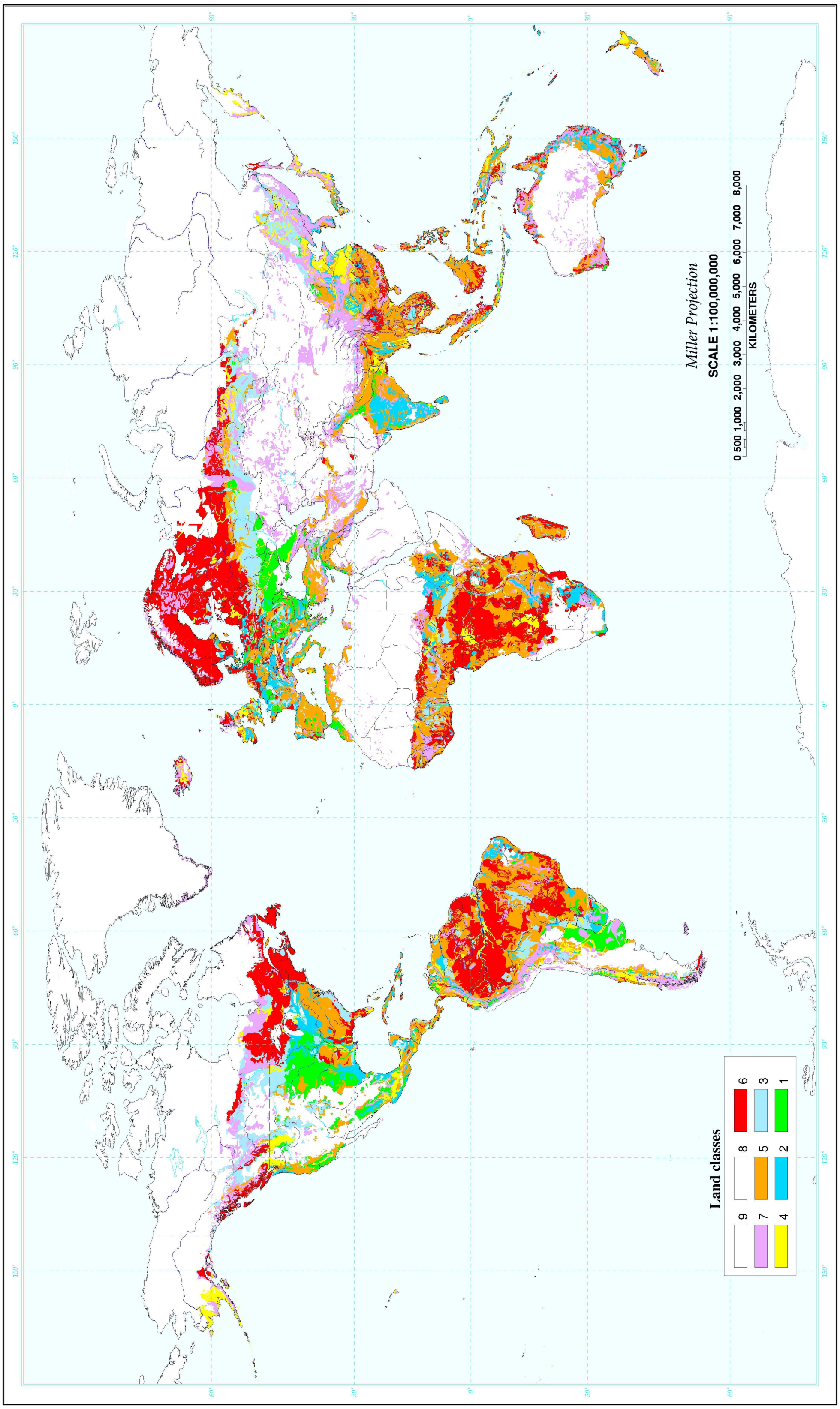
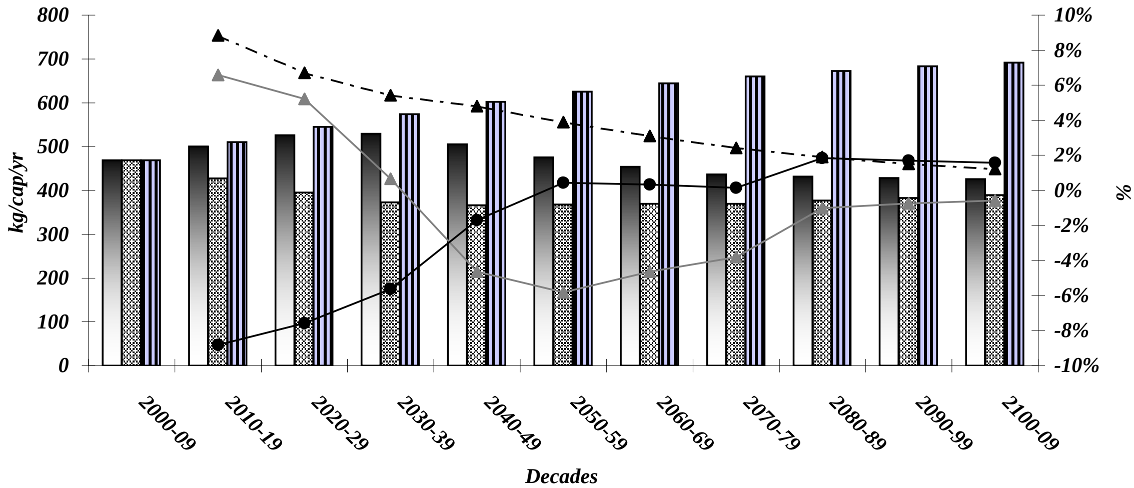


Figure 5: **Inherent land quality**

<u>Source</u> : *Wiebe (*2003*, p.* 121*)*

Figure 6: **Annual per capita demand for each food product and their growth rates**

Vegetarian products



Animal protein products

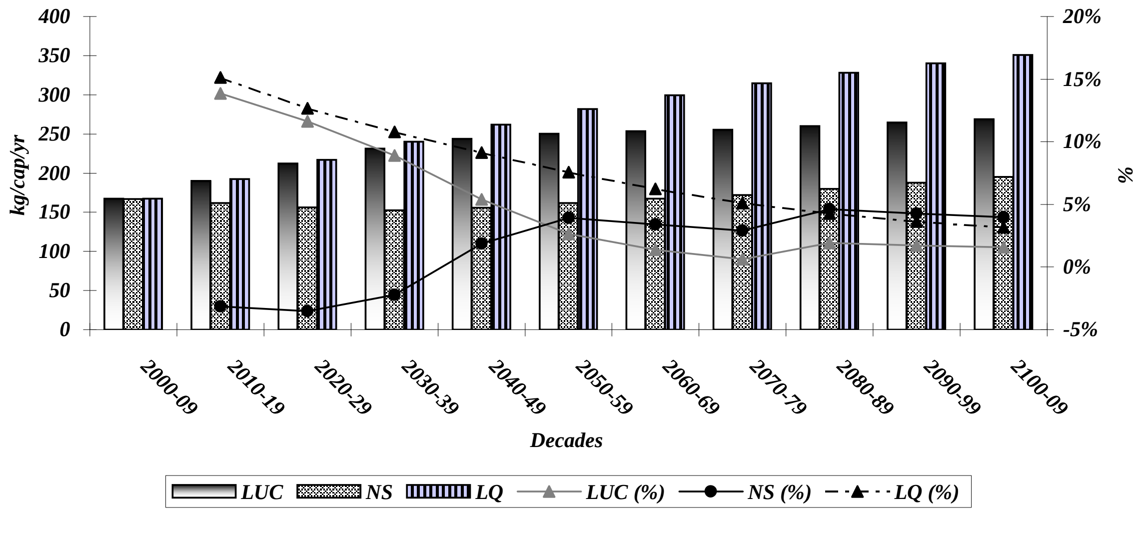


Figure 7: Optimal agricultural land allocation

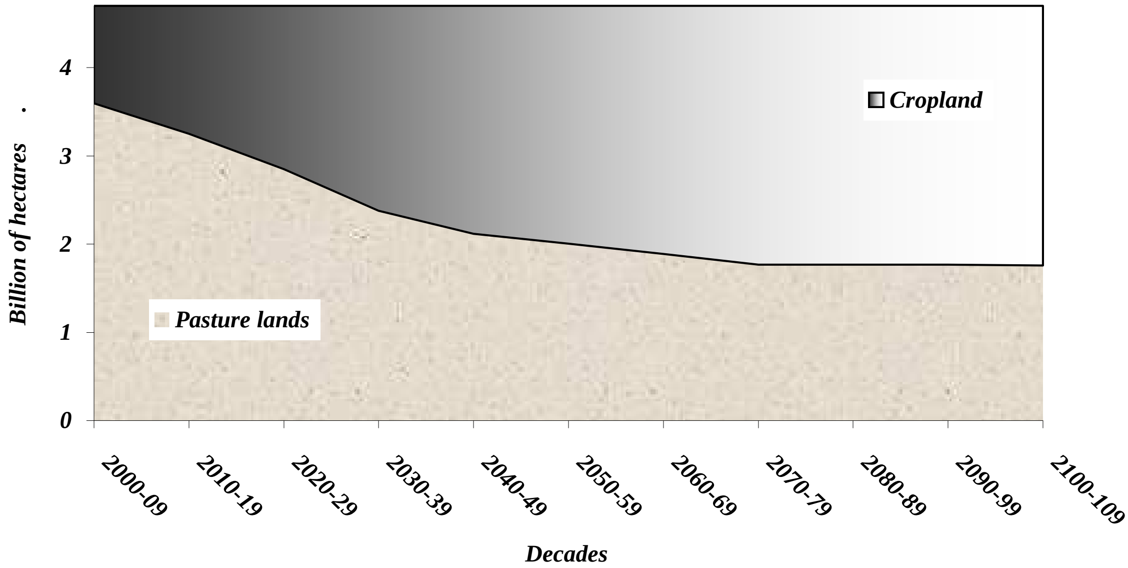


Figure 8: Percentage of total primary production stemming from each land class

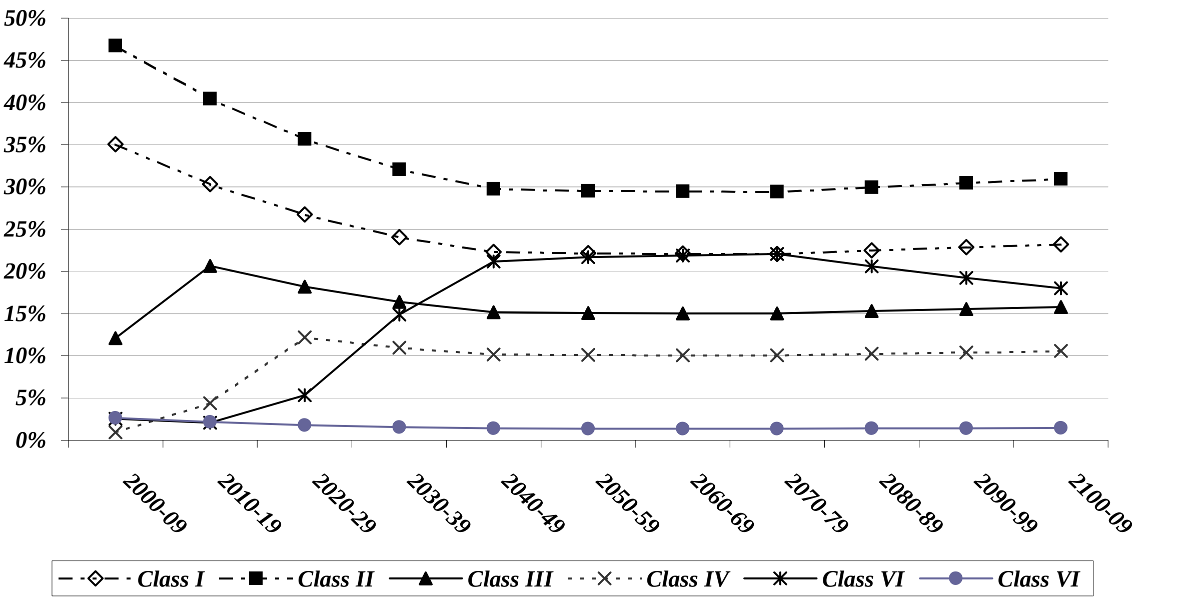


Table 2: Land allocation of the different land classes

	Global land surface		Agricultural area		
Land Class	**Billion of hectares**	**% of the global surface**	**Billion of hectares**	**% of agricultural area in the class**	**% of the total agricultural area**
I	*0,41*	*3%*	*0,40*	*98%*	*9%*
II	*0,65*	*5%*	*0,60*	*92%*	*13%*
III	*0,59*	*5%*	*0,59*	*83%*	*10%*
IV	*0,51*	*4%*	*0,51*	*80%*	*9%*
V	*2,41*	*18%*	*2,41*	*54%*	*28%*
VI	*1,72*	*13%*	*1,72*	*87%*	*32%*
VII	*1,17*	*9%*	*0,00*	*0%*	*0%*
VIII	*3,70*	*28%*	*0,00*	*0%*	*0%*
IX	*2,18*	*17%*	*0,00*	*0%*	*0%*
Total	**13,06**	**100%**	**4,70**		

Table 3: **Primary agricultural yields with respect to each land class use.**

			Primary crops yields			
			(tons of crops per hectare)			
Decade	**Class I**	**Class II**	**Class III**	**Class IV**	**Class V**	**Class VI**
2000-09	*4,50*	*4,00*	*2,50*	*2,00*	*1,50*	*0,90*
2050-59	*6,76*	*6,00*	*3,75*	*3,00*	*2,25*	*1,35*
2100-09	*7,96*	*7,07*	*4,42*	*3,54*	*2,65*	*1,59*
			Intensive livestock system yields			
			(tons of livestock per hectare)			
Decade	**Class I**	**Class II**	**Class III**	**Class IV**	**Class V**	**Class VI**
2000-09	*1,80*	*1,60*	*1,00*	*0,80*	*0,60*	*0,36*
2050-59	*2,70*	*2,40*	*1,50*	*1,20*	*0,90*	*0,54*
2100-09	*3,18*	*2,83*	*1,77*	*1,42*	*1,06*	*0,64*
			Grazing system yields			
			(tons of livestock per hectare)			
Decade	**Class I**	**Class II**	**Class III**	**Class IV**	**Class V**	**Class VI**
2000-09	*0,20*	*0,17*	*0,14*	*0,12*	*0,10*	*0,09*
2050-59	*0,25*	*0,21*	*0,18*	*0,15*	*0,13*	*0,11*
2100-09	*0,30*	*0,25*	*0,21*	*0,18*	*0,15*	*0,13*

Table 4: Patterns of food prices.

Vegetarian products						
	Prices ($/ton*)			Decennial percentage change		
Decades	**LUC**	**NS**	**LQ**	**LUC**	**NS**	**LQ**
2000-09	300	301	300			
2010-19	309	777	273	3%	158%	-9%
2020-29	318	1 717	259	3%	121%	-5%
2030-39	400	3 159	248	26%	84%	-4%
2040-49	655	4 335	233	64%	37%	-6%
2050-59	1 107	5 023	221	69%	16%	-5%
2060-69	1 673	5 634	210	51%	12%	-5%
2070-79	2 329	6 183	202	39%	10%	-4%
2080-89	2 670	5 997	195	15%	-3%	-4%
2090-99	2 960	5 756	189	11%	-4%	-3%
2100-09	3 203	5 489	183	8%	-5%	-3%

Animal protein products prices						
	Prices ($/ton*)			Decennial percentage change		
Decades	**LUC**	**NS**	**LQ**	**LUC**	**NS**	**LQ**
2000-09	3 923	3 930	3 923			
2010-19	3 944	8 919	3 731	1%	127%	-5%
2020-29	3 966	18 900	3 573	1%	112%	-4%
2030-39	4 159	34 767	3 429	5%	84%	-4%
2040-49	4 766	48 256	3 280	15%	39%	-4%
2050-59	5 839	56 494	3 141	23%	17%	-4%
2060-69	7 184	63 763	3 012	23%	13%	-4%
2070-79	8 741	69 988	2 891	22%	10%	-4%
2080-89	9 550	67 659	2 778	9%	-3%	-4%
2090-99	10 240	64 488	2 671	7%	-5%	-4%
2100-09	10 816	60 899	2 570	6%	-6%	-4%

** The prices are expressed in constant value, the discount rate is equal to* 2% *(Gollier* 2002.*a and* 2002.*b)*

Table 5: **Land rents* in relation with land-uses, *scenario land use changes***

Decades	**Class I**		**Class II**		**Class III**		**Class IV**		**Class V**		**Class VI**	
	Rent	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**
2000-09	**447**	**crop**	**357**	**crop**	**238**	**crop/past.**	**218**	**pastures**	**180**	**pastures**	**162**	**pastures**
2010-19	**484**	**crop**	**391**	**crop**	**259**	**crop**	**220**	**crop/past.**	**182**	**pastures**	**164**	**pastures**
2020-29	**524**	**crop**	**426**	**crop**	**281**	**crop**	**238**	**crop**	**185**	**crop/past.**	**166**	**pastures**
2030-39	**872**	**crop**	**735**	**crop**	**474**	**crop**	**392**	**crop**	**301**	**crop**	**183**	**crop/past.**
2040-49	2244	crop	1955	crop	1237	crop	1003	crop	758	crop	458	crop
2050-59	4633	crop	4078	crop	2564	crop	2064	crop	1554	crop	936	crop
2060-69	7861	crop	6948	crop	4357	crop	3499	crop	2630	crop	1581	crop
2070-79	11872	crop	10513	crop	6585	crop	5281	crop	3967	crop	2383	crop
2080-89	14470	crop	12822	crop	8029	crop	6436	crop	4833	crop	2903	crop
2090-99	16900	crop	14983	crop	9379	crop	7516	crop	5643	crop	3389	crop

**The land rents are expressed in constant value, the discount rate is equal to 2% (Gollier 2002.a and 2002.b)*

NB: The figures in bold represent the period over which the substitution between the two livestock production systems is used to rise world agricultural production.

Table 6: **Land rents* and land-uses,** ***scenario : land quality***

Decades	**Class I**		**Class II**		**Class III**		**Class IV**		**Class V**		**Class VI**	
	Rent	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**	**Rent**	**Use(s)**
2000-09	447	crop	357	crop	238	crop/past.	218	past.	180	past.	162	past.
2010-19	442	crop	353	crop	236	crop/past.	215	past.	178	past.	160	past.
2020-29	475	crop	382	crop	254	crop	216	crop/past.	179	past.	161	past.
2030-39	509	crop	412	crop	273	crop	231	crop	180	crop/past.	161	past.
2040-49	505	crop	409	crop	271	crop	227	crop	178	crop/past.	160	past.
2050-59	503	crop	407	crop	269	crop	226	crop	178	crop/past.	160	past.
2060-69	500	crop	404	crop	268	crop	225	crop	177	crop/past.	159	past.
2070-79	497	crop	402	crop	266	crop	224	crop	176	crop/past.	158	past.
2080-89	495	crop	400	crop	265	crop	222	crop	175	crop/past.	157	past.

**The land rents are expressed in constant value, the discount rate is equal to 2% (Gollier 2002.a and 2002.b)*

Table 7: Computation of the relative error for key variables.

	Vegetarian products			Animal protein products		
	Annual per capita demand (kg/cap/yr)					
Decades	**Projected**	**Observed**	**Er**	**Projected**	**Observed**	**Er**
1960-69	347	359	-3%	105	110	-4%
1970-79	393	368	7%	121	115	6%
1980-89	433	384	13%	137	120	14%
1990-99	455	408	12%	147	124	19%
	Annual global demand (tons/yr)					
Decades	**Projected**	**Observed**	**Er**	**Projected**	**Observed**	**Er**
1960-69	1,171	1,198	-2%	0,355	0,367	-3%
1970-79	1,536	1,478	4%	0,474	0,459	3%
1980-89	2,012	1,844	9%	0,636	0,577	10%
1990-99	2,475	2,299	8%	0,801	0,698	15%

	Agricultural land allocation					
	Crop cultivation			Pasture land		
Decades	**Projected**	**Observed**	**Er**	**Projected**	**Observed**	**Er**
1960-09	1,243	1,391	-11%	3,177	3,145	1,02%
1970-79	1,299	1,43	-9%	3,341	3,21	4,08%
1980-89	1,392	1,482	-6%	3,308	3,292	0,49%
1990-99	1,415	1,586	-11%	3,485	3,422	1,84%