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AND FUTURE FOOD CONSUMPTION PATTERNS

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Climate Change Mitigation and Future Food Consumption Patterns

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Abstract

Discussions on climate change increasingly emphasize the contribution of agricultural activities to anthropogenic greenhouse gases emissions. In this paper, we investigate from a supply to demand side perspective the stress between food demand and climate change challenges up until 2030. We examine how more stringent climate change mitigation policies could alter agricultural markets and put at risk the nutrition possibilities of populations. We use for this purpose GLOBIOM, an applied partial equilibrium model covering, at the world scale and a fine grid resolution, the main land-based sectors: agriculture, forestry and bioenergy. For this exercise, the model is fully linked to a semi-flexible endogenous demand system with non-linear Engel's curves. Our results show that although forest related measures could be efficiently deployed without harming food security, a scenario of massive development of bioenergy would have more tangible impacts on food availability. Our most constraining option is a decrease in emissions from cattle, which would impose a reduction in the consumption of ruminant meat and milk. We illustrate that considering the current dynamic of consumption patterns, these latter policies, if implemented on the supply side directly, could have very uneven effects to the world's diet and harm primarily developing countries.

JEL Codes: C61, Q11, Q24, Q54.

1. Introduction

According to FAO, world food consumption should increase by 250 kcal/cap/day (+9%) by the year 2030 (Bruinsma 2003; Alexandratos, 2006). In particular, demand per capita for meat could increase by 27% and milk and dairy by 17% for the world average. As population will grow by more than two billion, the resulting 70% increase in demand will require an improvement of yield and conversion of new land into cultivated areas. Depending on the growth and yield assumption, cropland expansion could increase by 6 to 30% between 2000 and 2050 (Smith et al.; 2010). These changes will induce considerable additional greenhouse gas releases into the atmosphere.

Therefore, negotiations on climate change more and more consider the contribution of land use change (LUC) and land related activities for their high level of greenhouse gases (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC; 2007), agriculture would have been responsible for 5.1 to 6.1 GtCO2-eq of GHG emissions in 2005, which represents 10% to 12% of total anthropogenic GHG emissions. Deforestation alone would have added another 5.8 GtCO2-eq/year according to IPCC for the 1990s decade (Denman et al., 2007), whereas in total, the Food and Agriculture Organization quantifies to 1.8 GtCO2-eq the annual loss in global forests biomass during the more recent 2005-2010 period (FAO, 2010). In total the combination of these land use activities related to agriculture and forestry would have represented 30.9% of anthropogenic emissions (IPCC, 2007).

These trends suggest some future tensions between food demand and climate policy objectives. Developed countries have recently announced after the 15th Conference of the Parties under the UNFCCC some significant reductions of their GHG emissions in the medium to long run (EU up to -30% reduction of 1990 level by 2020 and USA -83% of 2005 emissions in 2050). In the overall strategy of climate change mitigation, these sectors appear particularly attractive because of their low abatement cost in comparison with industrial and energy sectors.

Designing policies balancing the food and energy security and the climate change mitigation challenges should therefore be a rising issue for the upcoming decades. This paper aims at exploring the impact of different mitigation policies on food consumption and diets.

Mitigation options for land use related activities are various. For agriculture, the most significant GHGs are CH4 from irrigated rice cultivation and livestock enteric fermentation (agriculture represent 50% of anthropogenic CH4 emissions) and N2O from fertilizer use

(60% of anthropogenic N2O emissions; IPCC, 2007). Some cost competitive options would allow saving 1500-1600 MtCO2-eq at prices as low as $20 per ton, mainly in developing countries (Smith et al., 2008).

On the forestry side, options would be even cheaper: deforestation could be reduced by 10% for $2-5 per tCO2 and by 50% for $10-21 USD (Kindermann et al., 2008). Beside deforestation, the opportunity to sequester carbon through afforestation and reforestation would also constitute a cost competitive alternative with $0.5 to $7 per tCO2 for forestry projects in developing countries (Richard and Stokes, 2004). Several international initiatives have been launched to support such mitigation actions, such as the UN Programme for Reducting of Emission from Deforestation and Forest Degradation (REDD) or the inclusion of Afforestation and Reforestation projects in the Clean Development Mechanism (CDM) under the Kyoto Protocol.

In parallel, new land related strategies have emerged targeting reduced emissions by substituting fossil energy with biomass products. Increasing the share of biomass in the energy mix has been promoted as an option for satisfying the electricity needs but also for transportation fuels with lower carbon emission intensity. The expansion of the biofuel sector in the US (20 Mtoe of ethanol in 2009; RFA, 2010) and in the EU (12.1 Mtoe in 2009; EUObserv'ER, 2010) diverted significant areas of crops previously used for food or feed in order to supply fossil fuel substitute and their coproduct. The effects of this policy has been strongly debated from an environmental perspective (Searchinger et al., 2008; Hertel et al., 2010; Al Riffai et al., 2010) as from a food policy one (Headey and Fan, 2009; Roberts and Schlenker, 2009). However, strong policies are nowadays in place that will let a significant share to first generation biofuels for at least the upcoming decade.

There is now a consistent literature studying the link between rising food demand and climate change challenges but most of it focuses either on the climate change impact on food production or on the impact of increased food demand on GHG emissions. Of course, many authors have investigated in detail the future trends in food demand to anticipate the pressure on the production system. Main drivers for future evolution are now well identified: future population increase, economic growth, food diet preferences, urbanization, income distribution and trade policies are the most important (see for reviews Kearney, 2010; Hawkesworth et al., 2010). The impact of a change in diet on the supply side and their environmental effects has been scrutinized by some recent work. For example, Erb et al.

(2009) show how diet change could help achieving organic farming and environmental sustainability without endangering food security. Stehfest et al. (2009) argue that a global transition to a low meat diet could halve the cost of mitigation for climate change by 2050. Popp et al. (2010) quantifies the impact of the shift in demand towards more meat would increase GHG from agriculture by 76%.

However, only few studies precisely address the question from a supply side angle with a mitigation perspective: what would be the impact on diet of some selected mitigation strategies on the production side? A technical reason for this is that GHG accounting requires large bottom up models that often do not incorporate an endogenous demand system (for example for the three latter references). Eickout et al. (2009) attempt to incorporate some elements of a detailed grid level land use model in a Computable General Equilibrium model with an endogenous supply curve and exchanging information between the two models. But their description of agricultural production remains finally very close to the top-down aggregated structure of a standard GTAP-based model.

In this paper, we propose to bridge this gap by investigating empirically the tension that will arise between food demand and climate change challenges, between today and 2030, from a supply side perspective with a detailed analysis on their effect on demand. For this, we develop an innovative full linkage between a partial equilibrium model, GLOBIOM (Havlík et al, 2010) and an endogenous demand system of rank 3 incorporating own and cross-price substitution and non linear income elasticities based on a semi-flexible nested LES-CES structure. This design allows to more adequately measure changes in demand patterns in response to supply constraints, answering some critics from the economic literature on bottom-up approaches (Cirera and Masset, 2010) while keeping all the detail on production characteristics, costs and environmental variables of a grid-based model.

After having exposed possible baselines resulting from different preferences settings, we use this framework to analyze the effects of three different climate change mitigation policies on the nature and composition of diets across regions. First, a situation is considered where forest conversion to cropland is reduced on the period following the implementation of a funding mechanism under the REDD. Second, a scenario of world development of bioenergy is incorporated to assess their impact on food availability. Last, constraints on CH4 emissions from cattle are examined. We show that for the same level of reduction of emissions, the first policy has a very limited effect on food availability whereas the second one brings more alteration to the food demand and the last one has a dramatic effect, especially for emerging countries.

The paper structure falls as follows: in section two, the modeling framework will be presented with a quick overview of the different supply side features and a more detailed emphasis on the demand side developments achieved for this work. In a third part, the output of the model under different baseline assumptions will be exposed with its characteristics in terms of production change and associated emissions and change in the structure of demand in reaction to GDP and population evolution as well as price evolution. In the fourth section, we will present the impact of the three mitigation scenarios targeting three different sources of emissions or sequestration – CO2 from deforestation, biofuel emissions savings and cattle CH4 emissions respectively. The impact of these policies on the consumption patterns of different regions will be scrutinized. We will then expose our conclusions with respect to the different mitigation options, and discuss the strength and limitations of the approach to better understand the most desirable scenarios.

2. Modelling framework

2.1. The standard structure of GLOBIOM

GLOBIOM is an economic partial equilibrium model describing the main land-based activities: agriculture, forestry and bioenergy. It follows a spatial price equilibrium setting (SPE) where the maximization of producer and consumer surplus in all regions minus the transportation costs of all shipments, subject to resource, technological, and political restrictions gives the equilibrium quantities and prices for each region (Takayama and Judge, 1971; McCarl and Spreen, 1980). The main advantage of SPE models is the endogenous computation of bilateral trade flows without having to resort to the Armington assumption (Paris et al., 2009). It relies on the assumption of homogeneous goods so that the differences in prices from one region to another are only due to trading costs and barriers.

A full description of the main model characteristics can be found in Havlik et al. (2010). To summarize, the model directly represents production from four major land cover types, cropland, grassland, managed forest and areas suitable for short rotation tree plantations, by implicit product supply functions based on Leontief production functions. The supply side of the model is structured around a detailed spatial resolution (0.5 arcmin pixels) based on a global database which includes information on soil types, climate, topography, land cover and crop management (Skalsky et al., 2008) and on two biophysical models, EPIC for crops (Izaurralde et al.; 2006) and G4M for forests (Kindermann et al., 2006). Currently, 18 crops and 5 forestry products are included in the model, which can be used for food consumption, animal feeding or biofuel production.

Production quantities, producer prices, and total area at the country level were taken from the FAO. Spatial data on land use come from the JRC (GLC2000) and IFPRI for crop distribution map (You and Wood, 2006). Livestock production has been expanded to represent production of six different final products (4 types of meat, eggs and milk) through the production of 5 different animal species. Different livestock production systems have been designed based on ILRI/FAO nomenclature (updated Serre and Steinfeld, 1996) and populated with data using process based models for ruminants (RUMINANT – Herrero et al., 2008), and using literature review and expert knowledge for the monogastrics.

A common pitfall of empirical models is the discrepancy between observed trade flows and the trade flows generated by the model solution (Paris et al., 2009). We use an original method based on bilevel programming which has been developed by Janson and Heckelei (2009) to calibrate simultaneously producer prices, trade costs, and bilateral trade flows (see Mosnier et al., 2010). Trade flows come from the BACI database which reconciles COMTRADE data (Gaulier et al., 2008) and tariffs are taken from the MAcMap-HS6 database (Bouët et al., 2004).

2.2. The demand system module

For previous research, own price elasticities on demand were generally sufficient to estimate impact of some policy shocks mainly implemented exogenously on the supply side. But in order to answer the questions addressed in this paper, it was necessary to improve the demand side specifications.

GLOBIOM is an optimization model relying on linear programming methods and solved with a simplex algorithm. This design allows to resolve the model at a very refined resolution on the supply side, while keeping the world dimension and to take into account irregular supply curves reflecting the heterogeneity of production constraints. The consumer welfare is optimized at the same time as the producer welfare in the objective function following standard partial equilibrium relations:

$$\underset{\bar{\boldsymbol{Q}} \in Supply}{\text{Max}} WELF = \underset{\bar{\boldsymbol{Q}} \in Supply}{\text{Max}} (CS + PS) = \underset{\bar{\boldsymbol{Q}} \in Supply}{\text{Max}} \left(\int_0^{\bar{\boldsymbol{Q}}} \boldsymbol{P^D}(Q) d\boldsymbol{Q} - \int_0^{\bar{\boldsymbol{Q}}} \boldsymbol{P^S}(\boldsymbol{Q}) d\boldsymbol{Q} \right)$$

where *WELF* designates the sum of the producer (*PS*) and the consumer surplus (*CS*), $\bar{Q}$ the market quantity vector at the equilibrium, $\boldsymbol{P^D}$ the demand price for the consumer and $\boldsymbol{P^S}$ the production cost for the producer, and *Supply* is the space of feasibility of $\boldsymbol{Q}$ depending on the available factors and technologies.

The first equation can easily be linearized in the case of an isoelastic demand function because each price depends on the quantity of a single product; however, the problem becomes much more complex to introduce with cross price elasticities. That is why we decided to separate the problems in two components to be simultaneously solved. On the first hand, a supply system would optimize the producer side only:

$$\underset{\bar{\boldsymbol{Q}} \in Supply}{\text{Max}} PS = \underset{\bar{\boldsymbol{Q}} \in Supply}{\text{Max}} \left(\boldsymbol{P^D}(\bar{\boldsymbol{Q}}) - \int_0^{\bar{\boldsymbol{Q}}} \boldsymbol{P^S}(\boldsymbol{Q}) d\boldsymbol{Q} \right)$$

On the other hand, we choose to develop a non linear more refined demand system that will be solved independently following the relation on a demand utility *UT*:

$$\underset{\boldsymbol{P^D}(\bar{\boldsymbol{Q}}).\bar{\boldsymbol{Q}} \leq Rev}{\text{Max}} CS = \underset{\boldsymbol{P^D}(\bar{\boldsymbol{Q}}).\bar{\boldsymbol{Q}} \leq Rev}{\text{Max}} UT(\bar{\boldsymbol{Q}})$$

Both systems are developed in the same programming language and linked together by successive iterations in order to ensure the consistency of the solution. The supply module sends the dual information on prices to the demand module that computes a new demand in quantity and feeds back to the supply side (see Figure 1). The iterative process is executed until convergence is reached. However, because some products could have high supply own price elasticity, simple iterations had sometimes to be completed with a dichotomy approach to resolve the most unstable product per region price/quantity couples.

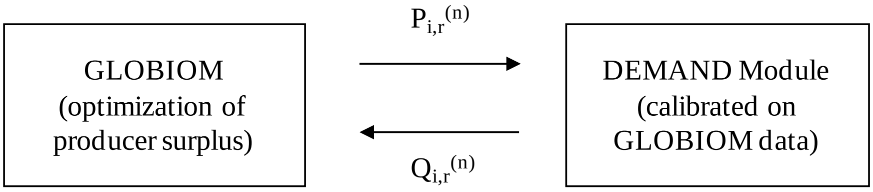

Figure 1. Structure of the linkage between supply and demand module. $P_{i;r}^{(n)}$ refers to the price of the good i in the region r for the iteration n. $Q_{i;r}^{(n)}$ refers to quantities.

Once implemented and tested, this design has the benefit of being able to link with the GLOBIOM model any demand system model as an external module. The demand we developed for this paper is a derivate of the Stone-Geary LES-CES, such as extended by Brown and Heien under the “S-branch” specification (1972). This system consists in several nested LES-CES levels whose minimum shares can be calibrated to fit income and price elasticities.

This functional form is semi-flexible which means that not all price and income elasticities can be calibrated at the same time but it has the advantage of being globally regular which appeared more suitable for a model with 10-year time steps and potentially large price shocks. This is why we preferred this approach to other forms used in econometric approaches such as locally regular AIDS or Rotterdam models. Although more complex demand systems such as AIDADS allow to reproduce sophisticated Engel’s curves profiles (see Yu et al., 2004 for an illustration), we could represent variations in income elasticities by recalibrating the system with yearly steps and reproduce the dynamic evolution of the Engel’s curves targeted baseline. The interaction between the supply and the demand is then solved every ten years, once the revenue per capita has been fixed, and after a recalibration of the demand side on price elasticities.

The structure of the demand substitution tree is illustrated in Figure 1. At the top level, the final consumer expenditure is represented with a substitution possible between two food aggregates (meat and vegetal calories), a fiber aggregate (only cotton in the current framework), a wood aggregate (Sawn wood and pulp paper wood) and a complementary good representing the rest of the consumption. The middle level of the tree represents substitution between vegetal calories aggregate (cereals, oilseeds, sugar, tubers and pulses) and the substitution between animal products aggregate (meat, milk and eggs). Last, the lower level is composed of CES functions that represent highly substitutable products such as different type of cereals (rice, wheat, barley) or meat (beef meat, sheep meat, pig meat, poultry meat).

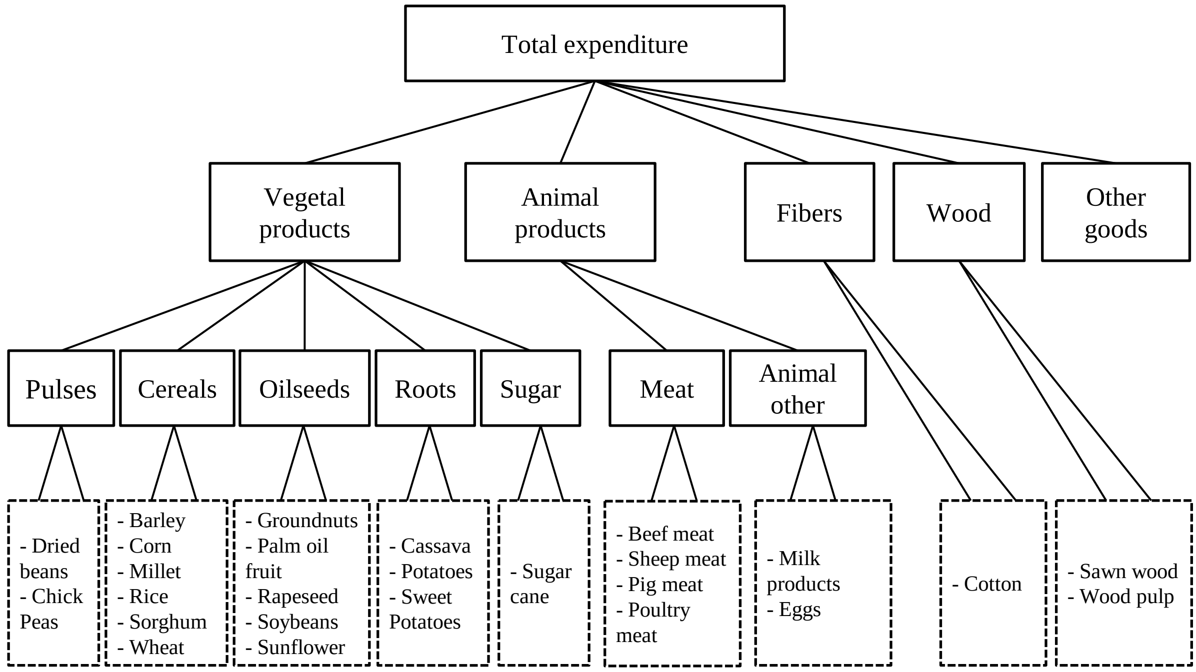

Figure 2. Structure of the nested demand system implemented. Plain boxes represent aggregates: LES-CES aggregates for two upper levels, and CES aggregates for the third level. The dashed boxes contain products represented on the supply side and which prices are demanded to the GLOBIOM supply side for a given quantity.

For elasticities used for the initial year, we relied on own-price and income elasticities provided by Seale et al. (2003). However, we also computed some income elasticities directly from FAO Food Balance Sheets (FBS) on the 1995-2005 period, and kept them when the goodness of fit was satisfactory ($R^2 > 0.5$). We considered for this as a first working assumption a simplified approach in which consumption patterns would evolve as a function of revenue only. More in depth econometric investigation on long time series could of course be helpful to distinguish a pure time effect from an economic growth effect but we preferred to get an estimate on short time periods around the base year.

Using our own elasticities from FBS allowed in particular to take into account some negative trends observed on the last decade (sugar in Japan, meat in Western Europe) that we introduced as negative income elasticities. As LES-CES systems do not allow to directly reproduce negative elasticities, we introduce these by adjusting price of concerned products with a tax indexed on the revenue per capita and recycled in the consumer revenue. Using this method allows to precisely reproduce the decrease of food demand with the income increase but has the drawbacks that it decreases the final utility of the representative agent; as we do not use this parameter for the convergence between the two models, this design appeared the most suitable.

3. Baseline assumptions and trends patterns towards 2030

3.1. Main exogenous drivers

The reference situation on which we run our simulations starts in 2000, the year of calibration and is computed by steps of 10 years until 2030. GDP and Population drivers are based on the last projections from the scenario "B2" of the Greenhouse Gas Initiative projections (IIASA, 2009). This scenario constitutes an intermediate between the higher and the lower bounds of established projections on world population and GDP. In the case of population, our reference value sticks to a world total 8.4 billion habitants in 2030, in which 4.8 billion in Asia and Pacific, 1.9 billion in Africa and Middle East, 1.2 billion in America and 600 million in Europe. On GDP side, the world annual growth projected represents an average 2.7% on the period, with 2.0% for developed countries and 3.7% for middle-income and least developed countries.

These patterns strongly structure the demand side as population influences the demand for food and indirectly for feed, whereas GDP growth shifts consumption patterns towards more consumption per capita and more meat input, as well as additional demand for fibers and for wood. Demand for bioenergy is based on the POLES model projections corresponding to an updated version of Russ et al. (2007). We introduce these projections as an exogenous demand that follows a heat and power generation increase by ten times between 2000 and 2030 up to 514 million tons of oil equivalent (toe) of dry biomass. Liquid biofuel programs are represented on their side with an increase from 10 Mtoe in 2000 up to 139 Mtoe by 2030 in first generation whereas second generation biofuels emerge by 2010 to reach 163 Mtoe in 2030.

On the production side, a very sensitive parameter is the change in crop yield. Although yield remains largely influenced by the endogenous allocation between production systems (subsistence; low input, high input, or irrigated), a pure technological yield increase is also considered exogenously along the baseline. As this parameter is highly uncertain and not the focus on this paper, we rely on an homogenous assumption of 0.5% of yield increase per year along the baseline for all the crops and for all regions.

Last, concerning trade policies and support to agriculture, although it is widely acknowledged that the policy evolution can play a significant role in the evolution of food prices, we do not investigate different scenario and assume a *status quo* on the period considered.

3.2. Consumption patterns

A main parameter of uncertainty we prefer to focus on in this part for studying possible profile of our baseline is the evolution of diets across the world. As many regions of the world emerge at a considerable pace, consumption patterns are likely to evolve in several possible directions which are not easily predictable. One can optimistically anticipate for a prolongation of the increasing trends in calorie intake per habitant across the world, even if some current consumption levels are significantly above what is considered as a healthy diet for a typical person. But the influence of cultural or religious trends, of changes in preferences, or of environmental resources related to each region also significantly shapes the evolution of consumption habits.

We will therefore examine in the rest of this part three possible evolution trends for developing regions and their consequences over the period. In the first trend that we call “Regional diets”, we assume that each region will keep a strong specific orientation in the composition of its food preference. Consumption level will evolve in accordance with current observed evolutions but the final target to be reached when the population enjoys a sufficient enough development level remains region specific. In a second framework, “Western diet”, we assume a convergence to a composition and intake level that corresponds to an average between EU and US diets. Last we take as a counterfactual a “Fixed diet” scenario where composition in diets would remain unchanged even under an increase in the total calorie intake. This scenario is however much less realistic as current evolution of diets invalidates it. However, it seems particularly interesting to examine this trend as counterfactual for the other alternatives.

Diets evolutions are implemented by changing the dynamics of income elasticities for the different regions. Initial income elasticities remain the same for all scenarios except if their sign is inconsistent with the target (possible for some regions for the western and the fixed diet scenario). We distinguish the case of OECD regions (corresponding in our aggregation to regions with GDP per capita over 20 000 USD in 2000) and non-OECD regions.

- For non OECD regions (below an average 20 000 USD per capita), we consider that diet consumption will evolve to attain a final mature and stable consumption pattern at the OECD average level of development. We set a target of 3600 kcal/cap/day (Higher European levels) for most regions except for Asia and Pacific where we consider 3400 kcal/cap/day considering the patterns observed in the most advanced of them (South Korea in particular).
- For OECD regions, the same approach is used but as the regions are already considered at a mature state, initial income elasticities observed in 2000 are kept very low and the consumption per capita is not supposed to evolve significantly. In particular, the two main outliers (USA with almost 3800 kcal/cap/day in 2007 and Japan with around 2800 kcal/cap/day) are supposed to remain close to their 2000 level of consumption per capita.

The methodology applied for each diet scenario is then the following:

- For the “Regional diet” scenario, we define the target diet of each country by extrapolating the current trends with the 2000 dynamic, under an isoelastic evolution. We use for each region the resulting diet composition and assume as before that it will be attained when the country reaches OECD-like income per capita level (35 000 USD per capita). This scenario therefore reflects strongly the dynamics of food changes with taking into account cultural and geographical characteristics.
- For the “Western diet” scenario, we set the same absolute targets than before in term of absolute intake but the distribution among food categories follows a simple average of the composition of USA and Western Europe diets (composed of North Europe, Mid-Western Europe and South Europe regions; Baltic Europe and Eastern Europe being therefore excluded).
- For the “Fixed diet” scenario, Calorie intakes in each food categories are then increased proportionally from the 2000 value to determine the level of consumption at the mature level. This assumption requires to discard some negative income elasticities from our dataset.

Differences in food patterns for major regions across the different scenarios are illustrated in Table 1. This table takes into account demand side only: real prices are supposed to remain stable and no substitution occurs due to supply constraint. For a better illustration of GDP per capita effects, two other scenarios from the GGI have been added. In a few words, the macro scenarios of A2r, B1 and B2 assume respectively low growth per capita, high growth per capita and intermediate scenario. Unsurprisingly, the total level of consumption reflects the increasing demand with the revenue per capita. The various scenarios show very different characteristics: in the fixed diet scenario, the demand for cereals increases significantly by 2030 because developing regions which already have a high level of cereals intake develop the fastest. This trend is reduced in the case of regional trends in diets, because emerging countries, such as China and Brazil, are reducing their dependency on cereals to consume superior food goods instead (oilseeds and vegetable oils, sugar, meat and animal products). In the western diet case, this trend is even reinforced, as countries converge to high level of intake of superior good and renounce even more on any dependency on cereals, roots or pulses.

Table 1. Different projections of world average diet depending on various macroeconomic and diet composition assumptions (kcal/cap/day).

Year	Diet	Macro	Cereals	Oilseeds and vege-table oils	Pulses	Root and tubers	Sugar	Meat	Milk, eggs and fat	Total (in model)	Others (not in model)	Total
2000	-	-	1366	297	56	146	190	215	208	**2478**	253	**2731**
2030	Regional	A2r	1380	392	66	182	255	240	223	**2738**	257	**2995**
		B1	1396	426	71	210	273	254	233	**2863**	272	**3135**
		B2	1392	420	67	204	265	253	228	**2831**	265	**3095**
	Western	A2r	1240	400	56	155	262	233	270	**2617**	246	**2862**
		B1	1196	437	48	161	282	256	312	**2692**	256	**2948**
		B2	1204	429	52	159	285	249	298	**2676**	251	**2927**
	Fixed	A2r	1533	340	73	180	227	215	214	**2781**	260	**3041**
		B1	1588	358	78	201	236	224	224	**2909**	274	**3183**
		B2	1581	353	77	197	231	222	218	**2880**	268	**3147**

This notion of targets may seem artificial because the idea of a hypothetical level of development at which diet requirements would not evolve is not empirically founded. In particular, we do not take into account with this approach the effect of aging of population, neither the change in income distribution that are likely to affect future food demand.

However, this approach is flexible enough to easily incorporate them in the future and combines several advantages. The main benefit of it is to decouple the uncertainty on growth (investigation field for the economist) and the uncertainty on food consumption preferences, (investigation field for the nutritionist). In particular, once the evolution of consumption pattern is assumed, such an approach can allow to track independently the revenue effects in policy shocks and their feedback effect on food demand. Targets used here are mainly illustrative and this framework is flexible enough to allow for different and more precise assumptions on targets per country while keeping the information on current income elasticities.

A second advantage is that this approach allows monitoring the real consistency of the overall food composition in the diet by defining consumption ceiling for calories intake per type of food. This is not always the case in more simple approaches relying on a fixed income elasticity or applying a quick rule of thumb for the decrease of this elasticity. For regions like China, it is for example possible that meat consumption per capita will experience a strong deceleration soon in the future considering that in 2007, consumption was already of 420 kcal/per/day (mainly from pork) against 450 kcal/per/day in the USA and 391 kcal/per/day in the European Union. But this deceleration may not be apparent already in the time series. Our approach allows to set first an assumption on what would be the level of consumption of pork and other type of meat in a mature China and only in a second step to derive the associated evolution of income elasticities.

3.3. Evolution of main indicators in the baseline.

For the following of the paper, we focus on the "Regional diet" assumption considering that this is the assumption that better reflects the initial income elasticities. However, from a pure prospective point of view, it is highly plausible that some trends in elasticities will drastically revert in the future and that the convergence to a "Western scenario" could be more relevant for some regions. For example, the income elasticity for cereals is still positive for Sub-Saharan African regions, but they are negative for some more advanced developing regions (North Africa and Middle East, China).

We compare the results of our baseline on demand with the projections from Alexandratos (2006) in Table 2. As stated before, our macro assumption is the "B2 scenario" and the world real GDP per capita is assumed to reach 8560 USD per capita (in 2000 constant value) from an initial 6100 USD per cap 2000 level. The total world average supply of calories for domestic consumption equals 3095 kcal/cap/day in our projections against 3040 kcal/cap/day for Alexandratos. Our world scenario "Regional diet" differs from Alexandratos's notably on three main factors. First, the different projections in growth at the regional level explain some significant differences. Alexandratos's world growth on the 2000–2030 period is assumed to be 2.1% whereas it is 2.7% in our scenario. In particular, growth is assumed to be 3.1% in

America Latina, versus 2.3% in Alexandratos on the period. Second, one can notice a smaller shift to animal products in our projections even if the increase remains significant. This is mainly the result of our regional diet assumption, that gives more place to the 2000 evolution trends. Therefore, regions where meat or milk demand increase remained very low in the recent decades are not assumed to converge towards a richer diet in these products, even under an assumption of higher growth (for example in South Asia or Africa). Last, for transition countries (former Russia and Eastern Europe States), we use approximately the same growth assumption as Alexandratos (4.5% on average on the period) but our income elasticities favor more significantly consumption increase, in particular in vegetal calories. These countries reach the same level of consumption as West Europe countries but keep a more vegetal products oriented profile because of our "Regional diet" settings.

Table 2. Comparaison of projections in calories/cap/day with extrapolation from Alexandratos (2006)

	Alexandratos (2006) 1999-2001		**Alexandratos (2006)** 2030		**Model** 1998-2002	**Model demand side** 2030	
	Total	Meat / Milk	Total	Meat / Milk	Total	Total	Meat / Milk
World	**2789**	**455**	**3040**	**548**	**2731**	**3095**	**518**
Developing countries	**2654**	**344**	**2960**	**458**	**2585**	**3010**	**440**
Sub-saharan Africa	2194	131	2600	180	2130	2541	160
Near East / North Africa	2974	292	3130	416	3134	3311	345
Latin America and Carribean	2836	558	3120	735	2795	3420	640
South Asia	2392	205	2790	350	2324	2701	263
East Asia	2872	470	3190	738	2761	3339	716
Industrial countries	**3446**	**945**	**3520**	**1019**	**3424**	**3562**	**973**
Transition countries	**2900**	**663**	**3150**	**821**	**2902**	**3529**	**781**

Notes: The projections from Alexandratos (2006) do not provide the detail per calories for meat and dairy products, only the evolution of quantity in kg per capita per year. Conversion for Alexandratos were done using the FAO FBS and take into account the composition effect between mik and meat but not within these aggregates. FAO FBS were updated progressively which explains the difference between the two 2000 columns (48 kcal/cap/day of difference at world level). Other regional differences in 2000 can be the result of mismatching between GLOBIOM regions and Alexandratos's aggregate. To avoid mismatch in calorie accounting for Meat/Milk demand, the model results presented here were computed in variation and applied to Alexandratos's estimated value.

However, the effect of intensification and technological progress on yield appears in our baseline to compensate the additional demand for crops. Prices indeed decrease for crops on the period by an average -9% between 2000 and 2030 although the land rent for most regions increases. On the animal product side however, the trend is different and the pressure on grassland in some regions particularly stimulate prices, +15% at the world level.

As a result, consumption levels differ slightly from the demand side projections in Table 2 when price effects are taken into account and final consumption is by 1% lower at 3052 kcal/cap/day whereas it was recorded by FAO to be 2630 kcal/cap/day in 1990, 2725 in 2000 and 2798 in 2007. The regional break-down with income and price effects is illustrated in Table 3.

Table 3. Food availability per region along the baseline according to the B2-Regional diet scenario (kcal/cap/day)

	Vegetal calories		Animal calories		Total calories	
	2000	**2030**	**2000**	**2030**	**2000**	**2030**
Australia - New Zealand	2088	2162	986	1011	3074	3173
Brazil	2249	2992	632	685	2881	3677
Canada	2568	2655	942	961	3509	3615
China	2339	2193	566	926	2905	3120
European Union (27)	2405	2505	1032	1060	3437	3565
Former Soviet Union	2190	2752	606	680	2796	3432
India	2157	2297	185	197	2342	2494
Japan	2215	2229	571	561	2786	2789
Mexico	2582	2930	577	718	3159	3648
Middle East & North Africa	2819	2971	315	334	3134	3305
Rest of Europe	2057	1872	873	1140	2929	3012
Rest of Latin America	2095	2805	491	560	2586	3365
Rest of South Asia	2025	2882	240	270	2266	3152
South East Asia & Pacific	2177	3047	229	340	2406	3387
South Korea	2573	2037	437	812	3009	2849
Sub Saharan Africa	2030	2442	145	165	2175	2607
United States of America	2716	2775	1019	1032	3735	3807
World	**2277**	**2545**	**454**	**507**	**2731**	**3052**

Note: Base 2000 values are computed using a 4 year average between 1998 and 2002. Results are different from Table 2 as price effect due to supply side response are now included.

On the supply side, this expansion of demand results in significant adaptation of the agricultural production. Cropland covered by the model expands by 169 Mha from an initial level of 929 Mha. In the same period, managed grassland expands from 1151 Mha in 2000 to 1189 Mha. The effect on primary/traditional? forest of this agricultural activities expansion amount -146 Mha on the period, which represents -5% of the forest area.

Emissions associated with these land use changes raise as a result of expansion of activities and because of the additional deforestation induced. We focus in this paper only on two large sources of emissions: CO_2 emissions from deforestation and CH_4 emissions from enteric fermentation in cattle. Additionally, we add for the analysis the CO_2 savings coming from substitution of fossil fuels by biofuels (1st and 2nd generation). GHG emission profiles at the horizon 2030 appear as shown in Figure 3. Deforestation appears as the large source of land-use related emissions with 1646 MtCO2-eq released per year, primarily in the Amazon Basin (830 MtCO2-eq) but also significantly in the Congo Basin (642 MtCO2-eq) and last in the Indonesian and Malaysian forests (170 MtCO2-eq). Enteric fermentation represents a slightly larger share of these emissions with 1989 MtCO2-eq per year, the major contributor being South America (458 MtCO2-eq) followed by some similar contribution of respectively Europe, North America, South Asia, Africa-Middle East and China-South-East Asia .

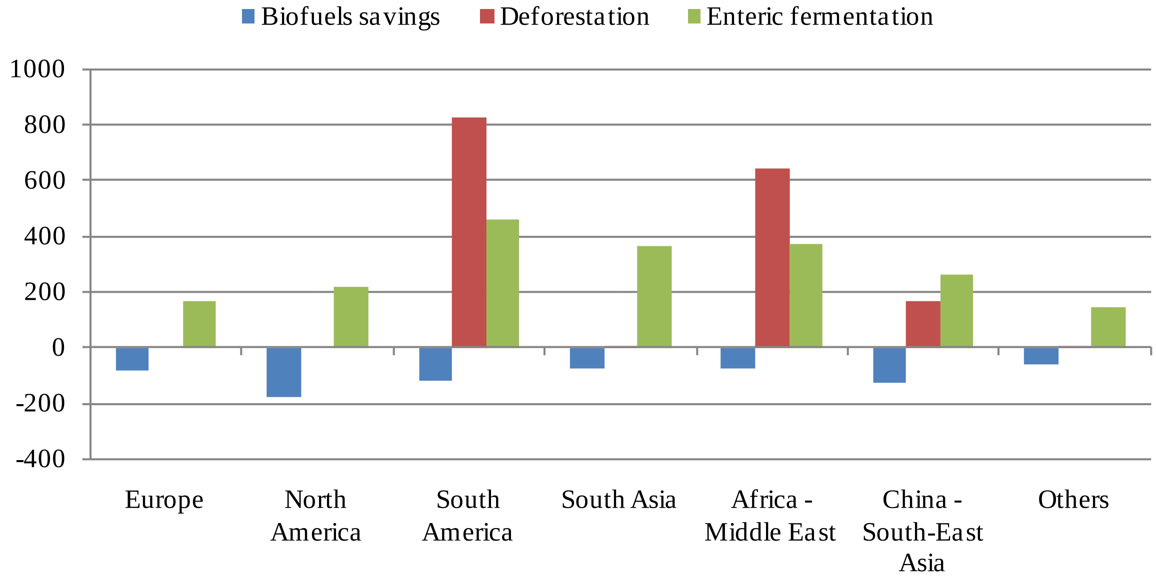

Figure 3. GHG Emissions in 2030 for the baseline scenario across three main categories of sources (Mt CO2eq per year). Results correspond to a “regional diet” scenario with low meat increase. “Others” corresponds to Former USSR, Japan, South Korea and Oceania.

These results on the baseline will be used as a basis to define the different mitigation scenarios to test and the amplitude of the reduction to target. However, they remain strongly dependant on the macro assumptions, especially for the deforestation results. In particular, as our “regional diet” scenario assumes an overall low increase in meat consumption in comparison with some more western oriented baselines (see Table 3), increase in grassland remains limited. Moreover, we do not consider here emissions from forest degradation nor emissions from soil carbon in peatlands. Consequently, deforestation emissions presented here (carbon contained in the above and below ground living biomass) are closer to the lower bound of most common estimates.

4. Mitigation scenarios and their differentiated impacts on prices and demand patterns

As exposed before, from a demand side perspective, the evolution of demand patterns along the baseline is mainly dependent on the increase in population and income per capita on the one hand and the evolution of aggregated preferences in reaction to cultural trends and policy incentives on the other hand. However, the capacity of the supply side to produce and deliver the desirable quantity of food also strongly matters. There is no doubt on the critical role that technology in agriculture will play to this respect, and considerable uncertainty exists on the extent to which innovation and progress in agriculture will allow to fulfill the challenge of feeding the world population. Of course, other environmental constraints will also be determinant such as water supply, land degradation, climate change, etc. However, the question we want to develop here is to what extent selected environmental policies could conflict with production objectives and impact the evolution of consumption patterns.

4.1. Scenario description

We develop in this part three climate mitigation scenarios where countries take provisions to limit GHG emissions from agriculture. We consider a first best situation where States would agree on a collective and optimized effort to curb these emissions by 500 MtCO2-eq per year at the world level, which would represent about 10% of abatement in agricultural or deforestation emissions on the basis of IPCC figures. In this cooperative approach, a financial instrument (similar to the REDD mechanism or a market of transferable carbon credits) would allow to transfer efforts from one region to another to best allocate the reductions of emissions across regions.

Three different scenarios are considered under this framework, targeting three different sources of GHG emissions or sinks for GHG sequestration (see Table 4). For each of these scenarios, the goal is to achieve the targeted reduction of emissions of 500 MtCO2-eq per year through the selected source only, and without possible leakage or shifting.

In the first scenario (MTG_FOR), emissions from net deforestation are targeted. These emissions weight in our baseline for 1444 MtCO2-eq per year on the 2010-2030 period and the effort therefore represents a 31% decrease in deforestation emissions across the world.

In the second scenario (MTG_BIOF), emissions savings are targeted through the expansion of biofuel use assuming that the substitution of biofuel with fossil fuel allows for a reduction in consumption of fossil fuel and therefore leads to GHG emission savings. Our baseline considers projections of biofuel consumption based on the existing programs under development. Our reference situation therefore envisages the production of 302 Mtoe of biofuels in 2030, in which 139 Mtoe crop based, resulting in a global saving of -280 MtCO2-eq per year by 2030 for first generation and -431 MtCO2-eq for second generation, on the basis of the life cycle analysis coefficients generally provided by official sources.[1] First and second generations remain both used in similar proportion. In total, the scenario considers an increase of savings from -329 to -829 MtCO2-eq on average per year on the 2010-2030 period, peaking at -1511 MtCO2-eq saved in 2030. The first generation sector grows under this framework by 91% whereas second generation pathway are 98% over their 2030 baseline target. This represents an average increase in global biofuels emission savings by 152% on the period.

In the third scenario (MTG_CTL), the livestock sector is directly targeted because of its significant methane emissions from enteric fermentation. Indeed, in our baseline, we project with the development of demand for meat and milk the expansion of total tropical livestock units of cattle (TLUs)[2] from 1.4 billion units in 2000 to 2.0 billion units in 2030, which would increase enteric fermentation emissions by 33% from the 2000 value of 1496 MtCO2-eq and lead to an average emission level of 1823 MtCO2-eq per year on the 2010-2030 period. Reducing the emissions by 500 MtCO2-eq would therefore imply a decrease of???? 27% of ruminant emissions.

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[1] The real savings associated to biofuels, especially first generation biofuels, are heavily debated among the scientific community. In particular, the contribution of N2O emissions from fertilizers and the indirect effect of land use change have be found in several works to at best question the overall benefits of diversion of food crops to biofuel use. In our approach, we take as a working framework a no leakage assumption and therefore prevent any additional emissions coming from deforestation or intensification. It therefore allows us to use official LCA figure. For the effect of indirect land use emissions with GLOBIOM, see Havlik et al. 2010.

[2] We follow the convention defined by FAO for accounting for livestock at an aggregated level. Tropical Livestock Units (TLUs) are defined as an aggregator for animals based on their feed requirements. In this framework, a head of cattle with a body mass of 250 kg approximately represents 1 TLU. For more details on this convention, see:
http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/Mixed1/TLU.htm

Table 4. Scenarios description and average emissions caps from selected sources in 2010-2030

		Emissions levels (MtCO2-eq per year)			
Name	Description	Defores-tation (CO2)	Biofuels savings (LCA)	Cattle (CH4)	**Total for considered sources**
BASE	Baseline	1444	-329	1823	**3118**
MTG_FOR	Reduction of global emissions from deforestation	**944**	-329	1823	**2618**
MTG_BIOF	Increase of global GHG savings from biofuel consumption	1444	**-829**	1823	**2618**
MTG_CTL	Reduction of global emissions from cattle enteric fermentation	1444	-329	**1323**	**2618**

The reduction objective of 500 MtCO2-eq per year is implemented after 2010 taking into account the increase in emissions along the baseline and the time necessary to implement progressively the policy. As a consequence, the largest part of reduction is achieved on the decade 2020-2030 as annual emissions are higher on this period. The overall distribution of reduction is implemented as follows: a progressive reduction from 0 to -600 MtCO2-eq per year in 2010-2020 (-300 MtCO2 average for the decade) and from -600 MtCO2-eq to -800 MtCO2-eq in 2020-2030 (700 MtCO2-eq average for the decade). Maintaining after 2020 the first rate of increase of abatement would have put a too high constraint on some sectors, and this assumption reflects indirectly the increasing cost of marginal abatement. For deforestation, cumulated emissions are decreased by 3000 MtCO2-eq on the 2010-2020 period and by 7000 MtCO2-eq on the 2020-2030 period.

The no leakage assumption for each of these scenarios also significantly structures the design of the scenarios envisaged. Indeed, aside from the reduction of objective for the selected source, it implies that other sources of emissions cannot exceed the baseline level, which introduces an additional constraint. For example, expansion of cropland into natural forests can be avoided through intensification of agriculture only under the assumption that, at the global level, the total intensification effect will not lead to additional emissions from fertilizers, even if some reallocation across sectors is possible. This can significantly influence the evolution of land use change and management practices chosen, and therefore the quantity of output produced although reallocations of emissions are allowed across regions. At the same time, we do not account for possible co-benefits of a mitigation policy, for example, the possible CO_2 saving from reduced deforestation related to a decrease in enteric fermentation emissions.

4.2. Impact of mitigation policy on supply and prices

Although they lead to similar level of reduction in emissions, the three scenarios considered have very contrasted results on production patterns and market prices.

The effects of the different policies on aggregate land use at the world level remain limited, as illustrated in Table 5. The main orientation of each mitigation scenario explains the pattern of differences observed. In the “MTG_FOR” scenario, the protection of forests leads to a significant increase in the area of primary forest (+ 26 million ha) and cropland expansion is slightly reduced (-4 million ha) and mainly diverted to expansion into grassland (-17 million ha). In the “MTG_BIOF” scenario, cropland expansion is higher because of biofuel expansion but remains of low magnitude (+-4 million ha) because of the no-leakage assumption that limits expansion of emission from intensive management practices and some reallocation between regions strongly affect natural land, whereas abandoned land increase in other parts of the world (not represented in Table 5). In the “MTG_CTL” scenario, the diminution in cattle head leads to a significant drop in grassland expansion (-74 million ha) because of the reduced requirement in grazing areas. This diminution of pressure saves a significant share of natural forest (+60 million ha) and to a lesser extent of natural land (+11 million ha). The area of deforestation prevented is more than twice larger than the one obtained in the “MTG_FOR”, scenario, which shows the possible co-benefits of the policies in term of GHG savings. However, the carbon intensity of these areas is lower than in the “MTG_FOR” scenario and as will be developed further, the effects on price and demand are more severe.

Table 5. Land use difference to baseline in 2030 under the different scenarios (million ha).

Land type	MTG_FOR	MTG_BIOF	MTG_CTL
Cropland	-4	-4	4
Grassland	-17	-9	-74
Forest	26	-11	60
Natural land	-6	-32	11
Short rotation tree plantation	0	57	-1

Cropland occupation at the world level remains at a magnitude close to the reference situation (1098 million ha) mainly because of the no leakage assumption and the inelastic demand for agricultural products. The distribution of cropland between regions is however different depending on the scenario (see Table 6). The "MTG_FOR" scenario very slightly affects cropland expansion because of the diversion of expansion to grassland. However, in the "MTG_BIOF" scenario, the expansion of biofuel production drives a huge expansion of cropland in Brazil, from 49 million ha to 67 million ha. Although this expansion of cropland area can at first sight appear a too strong response, it remains consistent with the zoning of the Brazilian government that plans to devote up to 64 million ha of land to sugar cane production in the long run, against around 8 million ha in recent years. However, our no leakage restriction leads to a decrease of production elsewhere, mainly in China, India, Southeast Asia and Sub-Saharan Africa. Last, the "MTG_CTL" scenario only marginally affects cropland, although one can observe a slight reallocation of cropland from China and India to Brazil and the EU27, where some rangeland has been freed.

Table 6. Cropland area[3] per region in 2030 under the different scenarios (million ha).

Region	BASE	MTG_FOR	MTG_BIOF	MTG_CTL
Brazil	49	46	67	49
China	123	124	123	124
European Union - West	41	41	40	40
European Union - East	23	23	23	23
Former Soviet Union	98	98	96	100
India	152	152	148	153
Mexico	19	19	19	19
Middle East & North Africa	64	64	63	65
North America	114	114	103	113
OECD Pacific countries	26	26	25	27
Rest of Europe	5	5	5	5
Rest of Latin America	50	50	53	50
Rest of South Asia	36	36	35	36
South East Asia & Pacific	94	93	93	94
Sub Saharan Africa	204	203	200	203
World	**1098**	**1094**	**1094**	**1102**

As a consequence, production is unevenly affected across regions and scenarios (see Table 7). As cropland expansion is only slightly affected in the "MTG_FOR" scenario, one observes limited effect on production at the world level. Among major cereals, corn, rice and wheat production are slightly decreased (-4.0, -1.3 and -1.1 million tons respectively) to the benefit

[3] Area of crops represented in the model.

of barley (+3.0 million tons). Soybeans cultivation is also marginally reduced (-0.6%) to the benefit of other oilseeds (+ 0.2% for rapeseed). However, the mitigation policy seems to have more effect on the cattle expansion, and ruminant meat production is more significantly reduced (-3.4% for bovine meat and -2.9% for sheep and goat meat). As a reaction, more non-ruminant meat is produced to satisfy meat demand (+0.5% for pig meat and +0.9% for poultry meat). Milk production is consequently affected by the decrease in cattle head (-2.9%).

Table 7. Deviation to production level achieved at the world level in 2030

	BASE	MTG_FOR	MTG_BIOF	MTG_CTL
	1000 tons	*% Var.*	*% Var.*	*% Var.*
Crops				
Barley	205776	1.5%	2.2%	3.8%
Beans dryed	36917	-0.4%	-1.2%	0.8%
Cassava	407293	-0.5%	-0.1%	-0.9%
Chick peas	19404	0.3%	-1.8%	5.5%
Corn	1115905	-0.4%	-2.2%	-0.7%
Cotton	60474	0.2%	-4.3%	2.8%
Groundnuts	78068	-0.2%	-0.6%	-0.4%
Millet	46627	-0.2%	-1.6%	-0.4%
Oil palm fruits	244494	-0.1%	-0.3%	0.0%
Potatoes	665102	0.1%	0.5%	3.7%
Rapeseed	138546	0.2%	-0.1%	0.7%
Rice	868512	-0.1%	-0.5%	-0.1%
Soya	223293	-0.6%	-1.7%	0.1%
Sorghum	108006	-0.3%	-1.9%	4.5%
Sugar cane	3830894	-0.1%	80.8%	-0.3%
Sunflower	23082	-0.2%	-0.3%	-3.7%
Sweet potatoes	325707	-0.1%	-3.1%	3.3%
Wheat	784020	-0.1%	-0.4%	0.0%
Animal products				
Bovine meat	83739	-3.4%	-0.7%	-29.9%
Sheep and goat meat	12611	-2.9%	-2.6%	-21.9%
Pig meat	149826	0.5%	-0.8%	3.5%
Poultry meat	116966	0.9%	-0.6%	5.5%
Poultry eggs	98665	0.0%	-0.5%	1.8%
Milk	767428	-2.9%	-0.3%	-7.1%
Wood products				
Wood for pulp	320893	0.0%	0.0%	-0.1%
Sawn wood	1049713	0.0%	0.3%	-0.1%

Effects are much more significant in the “MTG_BIOF”, considering that more cropland is devoted to first generation biofuel production to satisfy the requirement from the mitigation policy. The no leakage constraint drastically limits possibility of cropland expansion or intensification by use of more fertilisers, and production of food crops is therefore more impacted. Cropland at the world level is mainly challenged by sugar cane whose production is increased by 81%. Crops with high elastic demand such as cotton are the most impacted in relative terms (-4.3%) but cereals experience the higher drop in absolute quantities with -3 million tons for wheat, -25 million tons for corn and -14 million tons for rice. As a consequence, the entire animal sector is subsequently impacted through the supply chain. Pig meat production decrease by -0.8%, poultry meat by -0.6%. The requirement for land pushes for an intensification of cattle, and bovine meat decrease is limited to -0.7% whereas sheep and goat where limited intensification is possible decrease by a larger -2.6%.

The “MTG_CTL” provide even more contrasted results considering that it directly targets meat production from ruminant. The production of meat from cattle is therefore mechanically decreased and partly compensated by production of meat from non ruminant. The -27% average decrease in enteric fermentation emissions on the period, peaking at -40% of abatment in 2030, leads to the reduction of production in 2030 by -29.9% for bovine meat and by -21.9% for ovine meat for that year. Milk production is also seriously impacted but with a drop of -7.1% thanks to the higher yield of cattle for this product in intensive systems. As for the “MTG_FOR” scenario, this leads to a rebalancing in the meat sector and significantly more pig meat, poultry meat and poultry eggs are produced (+3.5%, +5.5% and +1.8% respectively) to compensate this loss for the consumer. Interestingly enough, the indirect impact on the crop sectors is very diverse, corresponding to the change required in the feed structure. This policy leads to an increase in the production of some cereals more specific to monogastric (3.8% for barley and 4.5% for sorghum) even if there is an overall decrease in demand for feed grain (-0.7% for corn). This is also compensated by an increase in feed roots and tubers (+ 3.7% for potatoes and +3.3% for sweet potatoes) whereas the no-leakage constraint limits the expansion of other crops (-1.0 million tons for rice).

Market prices reflect the trends observed on production constraints (see Table 8). The “MTG_FOR” scenario having little impact on production, it is not a surprise to see limited variation in price levels, with most crop price change within 1-2%. However, some specific price variation can also reflect the tension on certain regional markets following reallocation of some production. These tensions can in particular be more significant for some precise products. This is particularly the case for the sheep and goat meat market, which appears to strongly react to the mitigation policy (+4.7%). On the one side, intensification by change in systems less based on grazing is not considered in the model for sheep and goats. This partly explains why production of ovine meat was observed to drop more significantly than bovine meat, although both grazing types of animals are targeted by the policy. On the other side, bovine demand markets are more diversified than ovine demand markets and elasticities on meat that we use gives stronger reaction on developing markets more bovine oriented (higher elastiticies for America Latina than for East Asia).

Table 8. Change in average world Fischer price index observed in 2030 (USD per ton) Impact of mitigation policy on food consumption patterns

	MTG_FOR	MTG_BIOF	MTG_CTL
Crops			
Barley	1.8%	4.0%	1.9%
Beans dryed	0.8%	2.4%	-0.2%
Cassava	0.3%	0.8%	-0.1%
Chick peas	0.3%	1.0%	0.0%
Corn	0.8%	3.2%	0.3%
Cotton	1.2%	4.3%	0.3%
Groundnuts	0.4%	1.3%	-0.2%
Millet	1.1%	4.1%	-0.6%
Oil palm fruits	0.4%	1.0%	-0.1%
Potatoes	0.1%	0.2%	0.1%
Rapeseed	1.2%	3.6%	1.0%
Rice	0.5%	1.6%	-0.1%
Soya	1.6%	5.1%	0.4%
Sorghum	0.4%	1.3%	-0.1%
Sugar cane	0.2%	0.7%	0.0%
Sunflower	1.8%	3.4%	0.8%
Sweet potatoes	0.1%	0.3%	0.0%
Wheat	0.9%	2.3%	0.5%
Animal products			
Bovine meat	0.1%	1.1%	50.8%
Sheep and goat meat	4.7%	4.4%	42.7%
Pig meat	0.5%	1.7%	0.3%
Poultry meat	0.8%	2.0%	0.4%
Poultry eggs	0.3%	0.8%	0.1%
Milk	-1.1%	0.5%	37.8%

Effects are much more dramatic in the case of the mitigation through biofuels ("MTG_BIOF"). The competition for land already discussed triggers a general increase in prices (from around 2% to 5% for most). For this scenario, it is also noteworthy that price effects on the meat sectors are this time more evenly distributed because of feed price increase, ruminant meat is still increasing (by +1.1% bovine meat and +4.4% for ovine meat) but non-ruminant meat is also more expensive (+1.7% for pig meat and +2.0% for poultry meat). The joint production of milk is also affected by the drop in production, its price increase by +0.5%.

The last scenario (‘MTG_CTL”) has less impact on the crop sectors. On the one hand, more cereals and oilseeds previously used for feeding of cattle are in excess supply on the food market, which push prices downward; on the other hand, substitution of demand to pig and poultry meat increases the demand for some very specific types of feed. The two effects tend to compensate as most crop prices differ only in this scenario by around 1-2% maximum. On the meat sector side, price effects on ruminant meat are particularly significant, reflecting the reluctance of consumers to abandon consumption of this meat. Price of bovine meat increase by 51% and price of ovine meat by 43% which represents equivalent own price elasticities of -0.86 and -0.69 respectively. Milk prices also react strongly to the decrease in supply (+37.8%). The price response of the non-ruminant sector can appear lower than expected considering the significant increase in production that has been noted before. This is mainly the result of our modeling framework as all factor costs for the non-ruminant sectors are here linear. Therefore, as the prices of crops are little affected and no non-linear expansion costs are considered (to the difference of cattle whose expansion can be limited by land conversion costs), pig and poultry meat remain competitive even with a strong increase in production. This result is however possible only because significant quantity of feed has been made available following the decrease in ruminant meat production. The changes in prices and in food availability triggered by the different mitigation policies differently affect the consumption patterns. All scenarios do not have the same magnitude of effect, and the description of the previous section strongly let anticipate a limited effect in the scenario “MTG_FOR”, a slightly more significant effect for the scenario “MTG_BIOF” and a more dramatic change in the case of the “MTG_CTL” scenario.

Impacts on the total food availability at the world level are presented in Table 9. As anticipated, the effect of the deforestation mitigation policy remains very limited. The total calorie intake is diminished by only 11 kcal per person per day, distributed evenly between vegetal and animal calories decrease. Effects are however more significant in the “MTG_BIOF” scenario, because of the increase in the price of crops. Therefore, calorie intake for crops diminishes on average by 15 kcal per capita and per day, whereas animal calories only drop by 3 kcal per person per day, the overall change in consumption representing a drop of 18 of food availability on an energy content basis. The last scenario targeting the cattle sector drives the most significant shifts in consumption patterns. Meat consumption is considerably disturbed with a partial shift from ruminant meat to non ruminant meat and its aggregated consumption drops by 8 kcal per person per day at the world level thanks to a composition effect between calorie intensity of different type of meats (our substitution occurs on a weight basis and pork meat is more caloric than beef meat). Dairy products also reveal more expensive and their consumption decrease by 10 kcal. In total, place of animal products in the total diet is reduced by 19 kcal which represents a drop of 4%. The change in the prices of crops related to feed shifts does not affect significantly the food market and this scenario provides the most limited drop in vegetal calories (-2 kcal/cap/day).

Table 9. Calorie availability for food consumption in 2030 (kcal/cap/day)

	BASE	MTG_FOR	MTG_BIOF	MTG_CTL
Vegetal products				
Cereals	1338	1335	1330	1337
Oilseeds and vegetable oils	400	399	397	400
Roots and tubers	210	210	210	210
Pulses	67	67	66	67
Sugar	249	249	249	249
Other [1]	281	280	279	281
Total vegetal	**2545**	**2539**	**2530**	**2543**
Animal products				
Meat	257	256	255	249
Bovine meat	42	40	41	29
Sheep and goat meat	8	8	8	7
Pig meat	142	143	141	146
Poultry meat	53	54	53	56
Milk products and eggs	214	210	213	204
Other [2]	36	36	36	35
Total animal	**507**	**502**	**504**	**488**
Total calorie consumption	**3052**	**3041**	**3034**	**3031**

Notes: [1] in particular vegetable, fruits; alcools and stimulants; [2] in particular aquatic products, animal fat and offals.

When looking at the differentiated impacts per region, the inequality of impacts is striking although it varies a lot across scenarios. As an illustration, Figure 4 represents the loss in food available per capita in various regions. Three main factors determine the vulnerability of regions: first, the poorer is the region, and the more likely the increase in price will affect capacity of population to afford its food. For this aspect, we rely on price elasticities from

Seale et al. (2003).[4] A second criterion is the initial composition of food consumption in the region in magnitude and in composition. If more ruminant meat and milk is initially consumed, the region will be more affected than if animal production depends on pig meat or chicken meat and eggs. And as we assume in this scenario a regional specialization of diet, there is not a very significant shift in our baseline to more meat in Africa and Middle-East and East Asia consumption of meat stays on a composition close to its initial one (mostly pig and poultry meat). This explains why Brazil and Mexico are much more impacted than China. A third criterion comes from the cost structure of each country. If the market price is very high because of high transportation costs and trade barriers, the variation in prices can be very limited for some regions. This is made possible thanks to the structure of prices that are represented in absolute terms and not only in relative terms like for CGEs. Consequently, regions where market prices are very high remain quite insensitive to the shock.

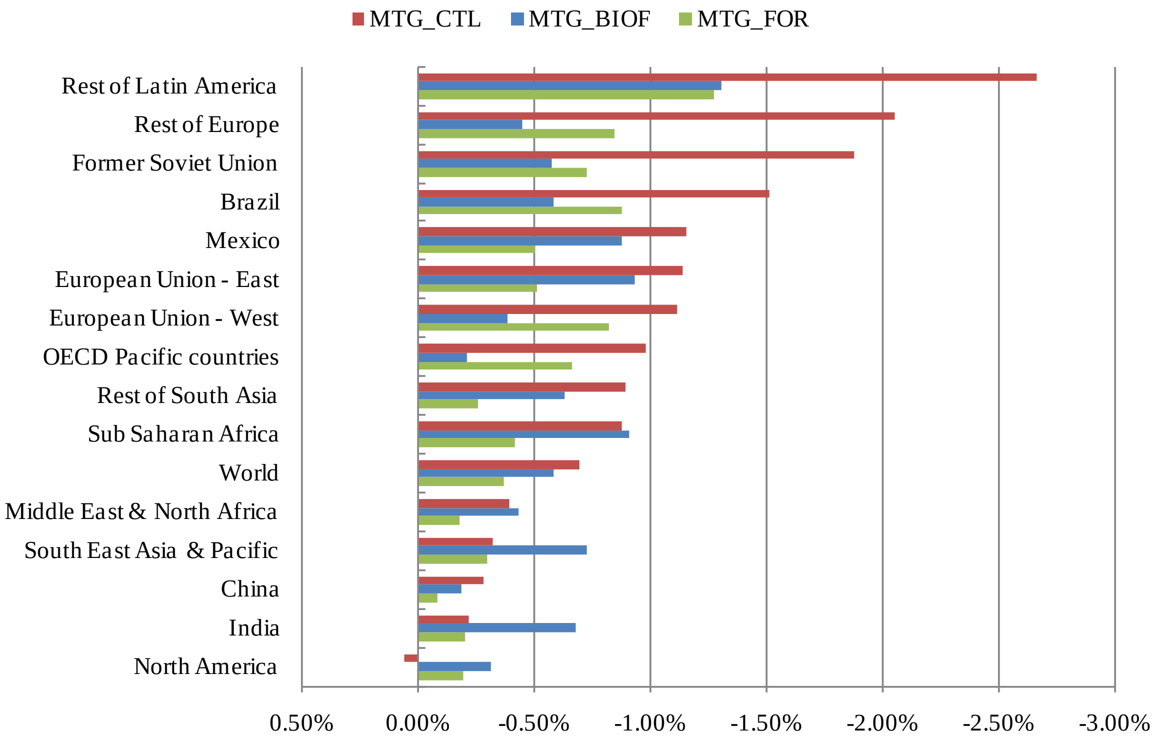

Figure 4. Decrease in total food availability per capita across regions in 2030 with reference to baseline. Countries are classified from top to bottom by decreasing order for the MTG_CTL scenario value.

[4] It is noteworthy that this source gives relatively high elasticities on meat aggregate for EU countries (-0.3 for West EU and -0.5-0.6 for Est EU, whereas the highest level is -0.7 for African countries), whereas it is very low for the US. This assumption is visible in the results as US are at the bottom of the table when sorting for the MTG_CTL scenario, whereas EU is in the middle.

The "MTG_CTL" scenario appears to be the one affecting the most in magnitude the world consumption (see Figure 5). Ruminant meat consumption decreases significantly (-30% for cattle meat and -21% for sheep and goat meat) and is only partially replaced by other meat types because of the increase in average price of meat. Overall, meat consumption decreases by 3% only because the structure of meat consumption is mainly relying on pigs and poultry in our projections. In the "MTG_BIOF" scenario, meat consumption is not affected and all the effect is coming from crops prices. The "MTG_FOR" scenario is between and milk consumption is notably affected at the world level (-3%). This effect on milk is all the more visible that milk cannot be easily substituted in the demand structure and that we assume very low cross-price elasticities for this product, in developed as well as in developing countries.

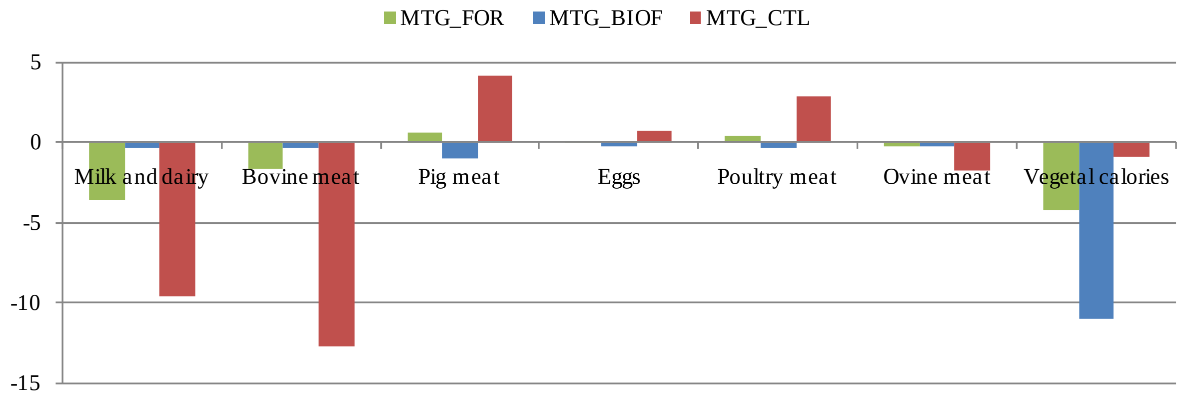

Figure 5. Difference to the baseline for calorie availability per capita per day in 2030 at the world level. "Other vegetal" and "Other animal" calories are not represented, only sectors in the model.

The representation of impact per region shows the diversity of possible effects depending on the initial structure of the diet. We show in Figure 6 the decomposition of animal calories for some developed and developing regions in the baseline and the "MTG_CTL" scenario. It allows to more precisely understand the diversity of effects. For example, in North America, meat consumption does not decrease because of a shift between meat types and calories are even found to increase in total (because of a composition effect between calorie content of different types of meat) even if the milk demand diminishes. For the EU the situation is similar, except that the composition effect is more limited and the price elasticities are higher on milk whose consumption decreases more substantially. That explains why demand decreases in the EU and not in the US in our modelling. China is little affected because it consumes in our "regional diet" scenario still very little beef in 2030. Impact in India is mainly occurring through milk and dairy but remains limited because of a low price elasticity for this product. Last Sub-Saharan Africa is significantly affected, as ruminant meat is traditionally consumed there and elasticities on the meat aggregate and on milk are much higher than for India.

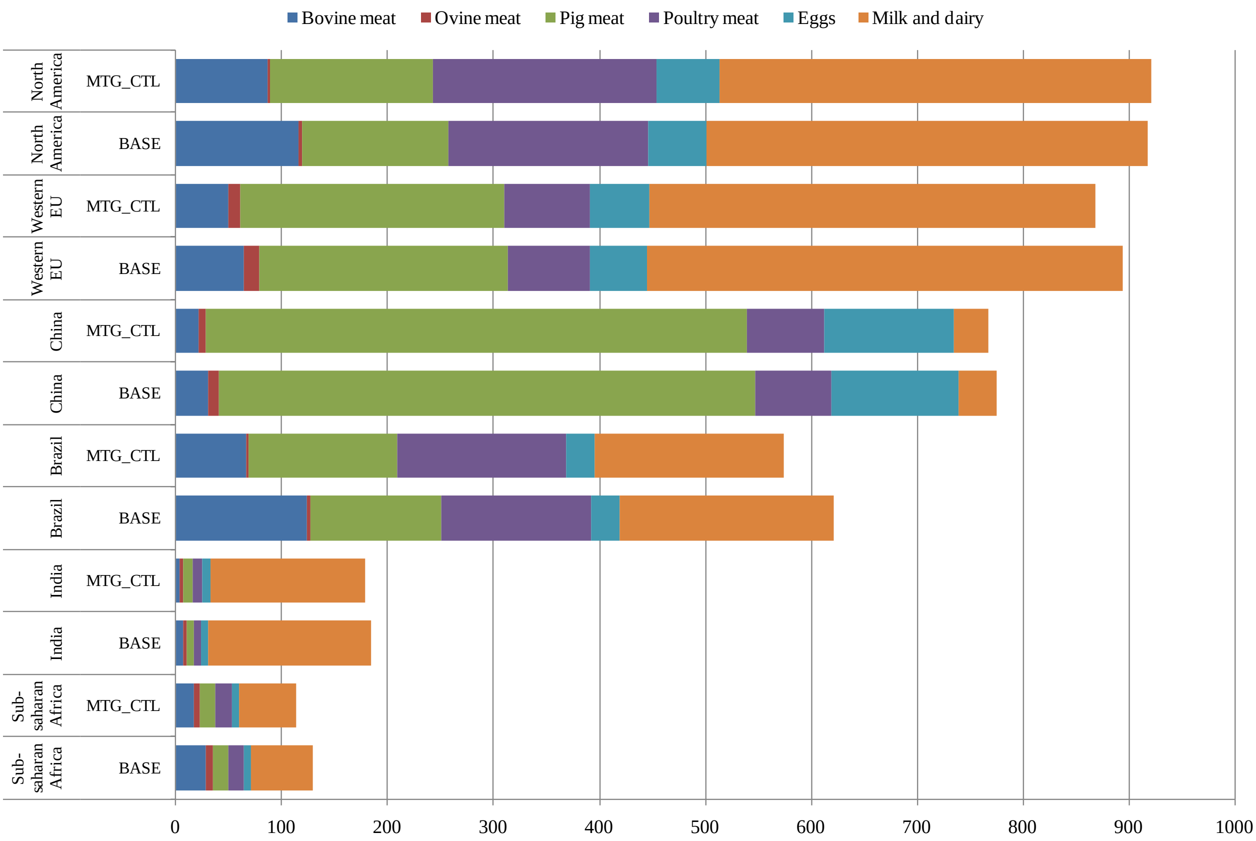

Figure 6. Calorie availability per capita per day in 2030 for selected regions in the baseline and the MTG_CTL scenario. The baseline is based on a “regional diet” scenario where no significant shift to more ruminant meat occurs. Fish and other animal calories are not represented.

On total, the redistribution of food between regions is particularly significant and the population factor accentuates the inequality observed per inhabitant, increasing the risk of troubles due to food insecurity (see Figure 6). The “MTG_CTL” scenario does not appear the most inequal scenario in terms of food availability as Western EU is part of the main regions impacted, mainly because of its very high consumption of milk based products. However, Africa and America Latina represent 48% of the losses for this scenario for 33% of the world population in 2030, most of them among the poorest. Similarly, in the “MTG_BIOF” scenario, Africa and India account for 46% of the overall decrease whereas they should only account for 7% of the world GDP in our scenario.

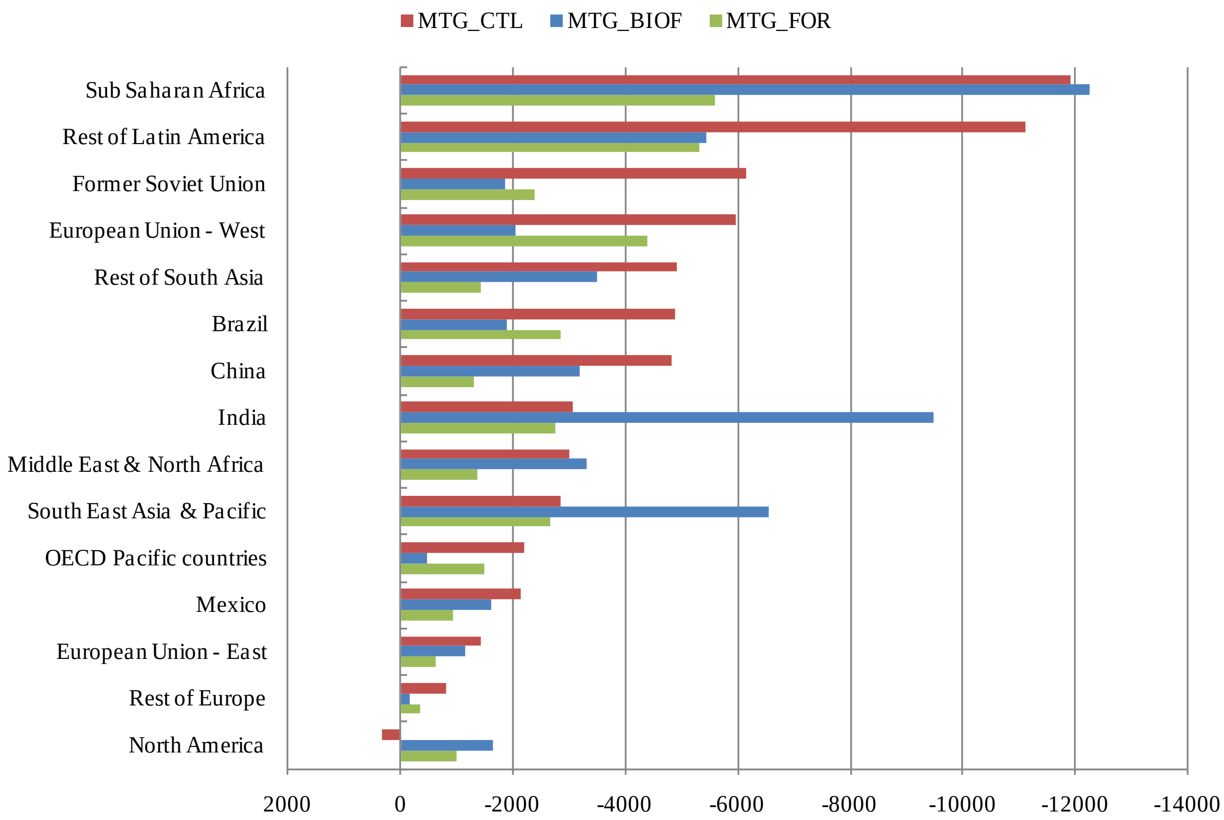

Figure 7. Food supply shortage for each region in 2030 expressed as difference to the baseline (billion kcal). Countries are classified from top to bottom by decreasing order for the MTG_CTL scenario value.

These patterns show the strong inequalities induced by such supply side policies, even if some advanced economies could suffer too in the case of an increase in milk price due to pressure on grassland or policies targeting cattle products.[5] These effects are even more adverse in terms of equity when crops are more affected as they should remain the main source of food for the poorest during the next decades. However, many emerging regions are also more and more consuming cattle meat and the sensitivity of these countries to mitigations policies is particularly effective. In particular, our study relied on an analysis of changes on an aggregated representative agent, which gives an illusion that a small increase in consumption per capita per day would still be sustainable. But in many developing countries, considering the distribution of income, such price distorsion would put significant number of habitants in situation of food unsecurity, by worsening an already vey unequal access to affordable food products.

[5] It is noteworthy that the main concern in West European Union countries during the food crises has been mainly the impact on the price of dairy products, for which the consumer of developed as for developing countries has little substitution possibilities.

5. Conclusion

Future food demand patterns will be strongly influenced by various macroeconomic variables (population increase, world wealth, urbanization speed) as well as changes in cultural and individual preferences. However, policies related to climate change mitigation could prove also influential if they target the most sensitive sources of land use related GHG emissions with respect to food security.

In this article, we showed, using a combination of a detailed bottom-up model and a flexible rank 3 demand system, that all mitigation policies would not have the same effect for the same target of abatement. These findings, although expected from a heuristic approach, needed to be put in perspective at a world level in a framework accounting precisely for GHG emissions. The final results we presented show how mitigation of emissions from deforestation could be a more desirable policy in comparison with a biofuel option or a livestock oriented option. These conclusions hold under the assumption that countries would coordinate to allocate their land for production needs more efficiently.

Biofuel policies could be a good candidate for mitigation, but forest plantations, short rotation coppices, and sugar cane plantations cannot sequester the same quantity of carbon as a natural forest, they do not constitute an optimal policy and impact more significantly food availability for the same level of reduction.

Similarly, policies targeting the meat sector because of its enteric fermentation emissions could be very harmful for the world welfare and more precisely the developing world, because it is a luxury product in these regions, although it provides essential nutrients for a healthy diet. Moreover, by increasing the price of milk, such policies would also impact the most advanced countries, and remove access of a very important product for a healthy diet to the poorest.

From a general perspective, we illustrated how targeting the agricultural production side directly by such policies would reinforce inequalities by imposing to all habitants the same level of constraint on food prices whatever their income level. At the same time, these policies would also harm differently the regions, depending on the composition of the diet. For example, Asia would be less impacted than Latin America in relative terms, as it relies less on ruminant meat and because rice is not the most sensitive product in land competition due to its specific cultivation requirements.

Although relying on a large set of recognized data, this analysis still relies on some structuring assumptions that should be kept in mind. First of all, in this analysis we still depend on an aggregated approach for demand. In particular, there is no consideration of poverty in developed countries and the effect of food price changes could also harm advanced economies with a high level of inequalities. In particular, we utilized a now dated, although widely used, set of elasticities. This information would need to be refined per regional case studies literature to reinforce the robustness of the results. Second, our baseline relies on a single assumption of GDP growth, preferences evolution and yield projections. The impact of climate change on yield, for example, is not taken into account even it is should remain limited by 2030. Therefore, different assumptions could lead to various effects across regions, although the main trends and the hierarchy between policies should remain the same. Third, land use change remains a complex dynamics to model and much remains to be done to improve the representation of activities such as deforestation or cattle ranching and their interaction with other land uses. Last, our no leakage assumption strongly structures the results. For example, not allowing for indirect effect from 1st generation biofuels significantly improve the efficiency of this mitigation option. Results would also have been significantly different if reallocation across regions of GHG abatements had been restricted.

Further explorations could therefore prolong this analysis and put it into perspective. The most obvious one is widening the range of mitigation policies studied which has been limited in this paper but could be extended to include sequestration from afforestation, nitrogen emissions or the targeting of other various sources. The sensitivity of the distribution of impacts to diet scenarios, and the role of inequality within countries also remain important paths to follow to better understand all of the implications of different mitigation strategies.

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