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BIOFUELS, AGRICULTURE AND CLIMATE CHANGE

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Abstract. **In the context of ever-increasing petroleum prices combined with concerns about climate change, timing of adoption and rate of diffusion of land-based fuels and backstop technologies for transportation use are examined in this paper. A global model of land allocation joined with a Hotelling model has been developed. Using this framework, effects of climate and energy policies on world agricultural and energy markets have been explored. Further, their regional impacts are also analyzed. Whereas mandatory blending bio-fuels have substantial effects on world food prices and do not succeed in curbing down carbon emissions fluxes, carbon targets are expected to speed up date of adoption of backstop technologies. Then, sensitivity scenarios with regards to technological parameters reveal that higher is the rate of technological change, earlier backstop technologies are adopted and lower is the stock of carbon accumulated into the atmosphere. Finally, interplay between land-based fuels and deforestation has been studied. Results show that land-based fuels production speeds up world deforestation and causes substantial carbon emissions due to conversion of forests into agricultural lands.**

Keywords— **Ricardian rents, land use, biofuels.**

I. INTRODUCTION

Concern about ever increasing concentrations of atmospheric CO2 and nearly exclusive reliance on non-renewable fossil fuels has sparked a search for alternative sources of energy, particularly for transportation. Transportation consumes one third of the global energy, 99% of which is supplied by petroleum that accounts for 21% of annual global greenhouse gas emissions. Further, two thirds of the increment in world liquids consumption is projected for use in transportation by 2030 (Rajagopal and Zilberman, 2007; IEA, 2007). Whereas a range of alternative energies such as nuclear power, wind and solar photovoltaic exist for the electricity sector, plant-based fuels (ethanol and bio-diesel) appear as the only alternative on the horizon that could substitute for petroleum in transportation. In contrast to biomass fuels, other technologies (fuel cell, electric/hybrid, and natural gas vehicles) are unable to compete widely with ethanol and bio-diesel on the basis of cost. Hence, agriculture should become a provider of energy along with food.

Meanwhile, around three billion people are expected to join the current population of six billion by 2050. Food production will have to rise to meet the increasing population induced demand, while with rising prosperity dietary patterns may shift towards a higher share meat and milk. Nonetheless, very few new arable lands are available for agricultural production (FAO, 2003). Besides considering land availability, land quality must be analyzed. Most of new available lands for agricultural production suffer from biophysical constraints such as fragile soils, too high or too low temperatures (Wiebe, 2004). Moreover, improvement in land quality through technological change should be lower than in the past (Rosegrant *et al.*, 2001).

Increasing scarcity of petroleum resources and land resources are evident. Further, they may be linked through bio-fuels development. Large scale bio-fuel production seems to be out of reach without hurting agricultural production. Implementation of bio-fuels policies in developed countries such as United-States had substantial consequences on world agricultural markets. In 2007, rises in agricultural prices have been spectacular, for example, oil palm prices have increased by 70% (New-York Times, 2008). Moreover, emission saving from the substitution of land-based fuels for fossil-fuels is fairly positive. Thus, increasing scarcity of petroleum and land may also be linked through climate policies. Thus, some questions arise: how energy policies aiming at developing bio-fuels production or climate policies aiming at fighting climate change should impact world agricultural sector? Since production of bio-fuels is not carbon-free, what could be their potential role in climate policies? What could be the impact of environmental regulation on the timing of adoption and rate of diffusion of first-generation biofuels and backstop technologies?

A first category of models analyzes the impacts of bio-fuels demand on agricultural markets. The International Model for Policy Analysis of Agricultural Commodities and Trade is a global partial equilibrium model built by the International Food Policy Research Institute (IFPRI). It aims to project future demand/supply balance as well trade for agricultural commodities in the medium term (Rosegrant, 2001). It has been enriched to focus on impacts of bio-fuels demands on calorie availability as well as on food security (Msangi *et al.* 2006). It reveals that without sufficient increase in crop productivity, aggressive growth in ethanol and bio-diesel supply should induce drastic rise in food prices and substantial decrease in food availability in some developing countries such as sub-Saharan Africa and South-Asia. These effects are softening when cellulosic ethanol technologies are adopted and productivity improvements realized. AGLINK-COSIMO is also a partial equilibrium model developed jointly by OECD and FAO for projection of future demand/supply balance and trade for agricultural commodities (OCDE, 2006). This study focuses on the analysis of policy changes with a special emphasis on domestic and trade policies. It also predicts substantial increase in food prices if bio-fuels mandates are imposed. The main drawback of these two previous studies is that they do not take account for implications of bio-fuels demand on land demand.

Schneider and Mc Carl (2003) have developed a land-use model of the US agricultural sector to examine the economic potential of bio-fuels in a portfolio of mitigation options and their implications for the US agriculture sector. For various carbon prices, they have determined the least costly mitigation options. Their results indicate no role for bio-fuels below carbon prices of 40$ per ton equivalent, but, for carbon prices higher than 70$ per ton equivalent, bio-fuels dominates all other strategies. The Schneider-McCarl study is regional and fails to take into account the effects of bio-fuel production on global trade and, hence, changes in energy and food prices. Further, by excluding the transportation sector, the authors ignore links between food-and-energy prices and bio-fuel production.

A second set of studies focus on agricultural sector together with energy sector. Reily and Paltsev (2007) have incorporated biomass technologies in a Computable General Equilibrium developed by MIT (EPPA, Emissions Predictions and Policy Analysis Model). Moreover, to take account for the effects of biomass energy production on agricultural and timber markets, competition for land have been incorporated in the model. Biomass energy can be used for avoiding greenhouse gas emissions from fossil fuels by providing equivalent energy services: electricity, heat and transportation fuels. Thus, different climate policies (greenhouse gas abatement, stabilization of greenhouse gas concentration, policy bio-fuels in the USA) have been defined. The study reveals that large scale production of liquid fuels from biomass should compete with land needed for food production and should induce significant increase in food prices. Even if this study is very detailed and may be an interesting policy tools, especially for the United-States, it fails in isolating economic trade-offs between producing food and energy.

Chakravorty *et al.* (2006) developed a dynamic model of land competition between food production and a clean land-based energy. The clean energy serves as a substitute to a polluting and exhaustible resource. Using their model, the authors explored the effects of environmental regulation imposed in the model as an upper-bound on the stock of pollution. This study gives interesting results and intuition about the effects of climate regulation that could be used in an empirical model.

In the current study, we couple a model of agricultural land allocation with a Hotelling model in order to analyze the effects of environmental regulation on food and energy markets. The joint model is calibrated at the global level over the next century in order to realize projections for world agricultural and energy markets when energy and climate policies are implemented. More precisely, it examines the trade-offs between allocating land to food production or to a clean land-based energy. Land is explicitly treated as a heterogeneous resource by defining different levels of land quality. The globe is divided into three regions: high income, medium income and low income countries. Regional demands for transportation can be satisfied either by crude oil or by a backstop technology. Regional agricultural sectors supply two aggregate food products (processed crops and animal protein products) plus bio-fuels. We use this framework to examine: (i) the impact of bio-fuels mandates and carbon targets on agricultural and energy sectors (ii) the impact of climate regulation on energy choices and on world agricultural sector. Nonetheless, bio-fuels production arises some other environmental concerns like deforestation and *its leakage effect*, these effects are analyzed by characterizing alternative scenarios. Finally, the timing of adoption and diffusion of bio-fuels depends dramatically upon some technologies parameters which are surrounded with uncertainties. Thus, two sensitivity scenarios with regards to main parameters: i) backstop technology production cost and capacity constraint and ii) elasticity of substitution between biofuels and petroleum are defined.

The paper is organized as follows. Section 2 presents the model. All the scenarios are described and their results are analyzed in section 3. Sensitivity analysis on the key parameters of the model is done in section 4.

II. MODEL

A. Final consumption

Growth in final demand is driven by regional population and regional per capita income. As per capita income rises, dietary habits are expected to switch towards more animal protein products. Thus, two final food products are distinguished, namely vegetarian and animal protein products. Since the bulk of increase in energy consumption should come from the transportation sector, we only consider demand for transport (IEA, 2007). Furthermore, petroleum in electricity and heat sectors has competitive substitutes like nuclear power, wind and solar energy. Share of bio-energy in electricity should not be significant.

Domestic demand for each final product takes the following form:

$$d_f^r = A_f^r . P_f^{\alpha_f^r} . y^{\beta_r} . N$$

$$f = \{processed\ crops,\ meat\ and\ dairy,\ transportation\}$$

$$r = \{rich, medium, low\}.$$

where r is the index for the different regions, d_f^r is regional demand expressed in billion of tons, P_f is commodity *f* price expressed in US$, α_f^r is the own-price elasticity of product f, β_f^r is the income elasticity for product f, y^r is the regional per capita income and N is the regional population expressed in billion of tons.[1] A_f^r is the constant demand parameter calibrated against observed data. To take account for changes in dietary habits, we suppose that income elasticity is not fixed across time and it is supposed to change with per capita income. Information related to demand functions is reported in Table 1.

Insert about here Table 1.
Insert about here Figures 1, 2 and 3.

B. Agricultural production

Since land properties differ dramatically across geographical areas, agricultural area is divided into different land classes which are characterized on the basis of their natural characteristics (soil and climate). Land quality is important for analyzing bio-fuels efficiency. Feedstock cost represents around 50% of land-based fuels production cost. Higher are land quality requirements, higher are bio-fuel production costs, and lower is bio-fuel efficiency. For instance, in Brazil bio-ethanol is obtained from sugar cane which can be cultivated on low land quality whereas in the United-States is produced from maize which more demanding in terms of land quality[2].

Classification established by the National Soil Services Resources of the United State Department for Agriculture (Wiebe, 2004) has been used to define different land classes. Whereas global land surface is divided into nine land classes in this database, we have put together land classes with similar characteristics[3]. Thus, we only have three land classes (see Table 2). Let us order them with index *i,* where *i* = *{high-quality, medium-quality, low-quality}*. Surface occupied by land class *i* is supposed to be constant and reported in Table 3. Each land type may be allocated to cropland or pastures. Let *u* be land-use index, where *u* = *{crop, pastures}*.

To meet increase in meat and milk demand induced by population growth in fast-growing countries, the general direction of change is towards intensification of livestock practices, which influences the composition of animal feed (Bowman, 1997, 2005). Indeed, this intensification is accompanied by decreasing dependence on open range feeding and increasing use of concentrate feed, which is expected to have important implications on land-use changes. The model aims to track the substitution between two livestock production systems, namely intensive-and-extensive systems. These two livestock production systems are supposed to be perfect substitutes. Within the extensive system land is allocated to pasture whereas it is allocated to crop production within the intensive system (see Figure 1).

USDA's database does provide data neither on agricultural yields nor on primary production costs with respect to each land-use and land class. Nonetheless, a country or a group of countries may be associated to each land class (see Figure 4).

Agricultural productivity and its growth rates are supposed to be exogenous[4]. Two types of agricultural yields have to be characterized. The first one is the primary crop yield or the number of crops produced on each land class. FAOSTAT database gives detailed information on primary crop production and yields at the country or regional level. Thus, primary crop yield with respect to each land class has been defined as a weighted average. The second one is the pasture yield or numbers of livestock per unit of land.

1. Regional per capita income as well as in regional population are pictured in Figures 2 and 3.

2. For example, Brazilian ethanol is economically viable when oil sells at $35 per barrel whereas U.S ethanol is viable only at around $50 per barrel (OCDE, 2006).
3. Further information on this data base is available in Appendix B.
4. Investment in agriculture is intrinsically linked with food prices. Over the last decades, investment in research and development for agricultural had been slowed down since food commodities diminished.

Bowman has developed several studies on livestock production systems at the world-wide level (Bowman 1997, 2005). Extensive livestock production system productivity has been defined for only developed and developing countries. Thus, we have associated data on developed countries to rich income countries whereas information on developing countries has been associated to medium and low income countries. Primary crop yields are expected to increase by 50% (respectively by 75%) over the next five decades (the century). Technological progress on pasture yields is supposed to be lower. Information on agricultural productivity is reported in Table 4.

As agricultural production increases, lower land quality classes are put into cultivation, more pressure is put on land resources. Thus, production cost rises. Regional total primary production cost with respect to use u in region r is defined by:

$$C_u^r(\sum_i y_{i,u}^r.L_{i,u}^r) = \eta_{1,u}^r\left(\sum_i y_{i,u}^r.L_{i,u}^r\right)^{\eta_{2,u}^r} \quad \forall u, \forall r$$

where $\eta_{1,u}^r$ *and* $\eta_{2,u}^r$ are specific regional parameters with respect to use u. Primary production costs can be extracted from GTAP and they are defined out of the cost of land. They are defined for different products and for different regions. As a next step, we have to calibrate function production cost using Mathematical Positive Programming (PMP).

Agriculture is expected to become a supplier of energy along with food. The model tracks competition between agricultural and energy uses of primary crop production (see Figure1).

Within the agricultural sector, primary crop production may be transformed into vegetarian products or into feed and forage products used within the intensive livestock production system. Regional coefficient of transformation of primary crop into processed crops is extracted from FAOSTAT. GTAP database gives information on transformation cost. Furthermore, number of meat and dairy products obtained per unit of crops which is commonly called the feed ratio is extracted from Bowman (1997, 2005).

Within transportation sector, primary crop production is directly transformed into a land-based fuel. Haiij *et al.* (2006) have defined conversion coefficients of feedstock into bio-fuels for different feedstock and bio-fuels. The choice of these parameters will be described more precisely in the next session.

Insert about here Tables 2, 3 and 4.

Insert about here Figures 4.

C. Energy Sector

Primary energy may be provided by three types of resources: an exhaustible resource and polluting resources: petroleum, renewable, space-consuming energy which also emits carbon but in a lesser extend: land-based fuels, finally, a renewable, no-space consuming and carbon-free resource: a backstop technology. There are indexed by k = *{petroleum, land-based fuels, backstop}*.

Each region is endowed with an initial stock of petroleum resource, denoted by $\overline{S}^r$. Different types of petroleum resources are available (crude oil, oil shale and bituminous sands)[5]. Furthermore, conventional resources and non conventional resources have been considered. Data on stock availability are extracted from the annual survey of World Council of Energy (WEC, 2007) and are reported in Table 5. Petroleum resources are used by different sectors such as transportation, chemical industry and heat. French Institute for Petroleum study indicates that 50% of petroleum resources are used by the transportation sector (IFP, 2007). Thus, we have only considered 50% of total resource available.[6] To take account for the heterogeneity of petroleum resources, regional extraction cost depends upon the cumulated amount of resource extracted at date t. This latter takes the following form (Nordhaus and Boyer, 2000):

$$C^r(s_t^r) = \xi_1^r + \xi_{\acute{e}}^r.\left(\sum_{t=0}^{\tilde{t}} s_t^r \Big/ \overline{S}^r\right)^{\xi^r}$$

where s_t^r is the amount of resource extracted at date t in region r and $\sum_{t=0}^{\tilde{t}} s_t^r$ is the cumulated amount of resource extracted at date t. The following inequality must hold: $\sum_{t=0}^{\tilde{t}} s_t^r \leq \overline{S}^r$. ξ_1^r is the extraction cost over the base-year, ξ_2^r and ξ_3^r are regional parameters. They are calibrated from SAUNER model database (European Commission, 2000). Parameters are reported in Table 5. Then, petroleum is converted into gasoline or diesel, the coefficient of conversion is uniform across the different regions. Impacts of energy choices on climate change are considered in the

[5] Moreover, we have considered inside each group all the grades.

[6] This assumption may be criticized since the bulk of increase in energy demand should come from transportation (IEA, 2007). Thus, this share is expected to increase.

model (DOE, 1997). Carbon emissions from fossil fuel combustion are reported in Table 6.[7]

Only land-based fuel is considered. Land-based fuels are classified into two categories, namely bio-diesel and bio-ethanol. Whereas the former is produced from cereals or sugar and sugar beets, the later is obtained from oil crops. Nevertheless, for a same land-based fuel, feedstock differs from a region to another. For instance, bio-ethanol is obtained from sugar-cane in Brazil whereas it is produced from maize in the United-States. To determine the regional coefficient of conversion of feedstock into land-based fuels, we have proceeded in the following way. First, we have defined a representative feedstock with respect to each land-based fuel in each region. Second, we have extracted the conversion coefficient from Von Lampe (2006). Third, we have computed the weighted average coefficient of conversion with respect to each region. To characterize the conversion cost of feedstock into land-based fuels, we have proceeded in the same way. Conversion costs have also been extracted from Von Lampe's studies. Subsidies have been included. Total carbon emissions resulting from bio-fuels production are extracted from studies called life-cycle assessment (IFP, 2007)[8]. They include all carbon emissions induced by bio-fuels production from *well to wheels*. All these parameters are reported in Table 7.

Finally, demand for energy may be also provided by no space consuming and renewable resource.

Several technologies may substitute petroleum resources. First, second generation of bio-fuels or lignocellulosic crops or residues are sill high and their energy efficiency is still low comparatively to bio-fuels of first generation. Second, electric and hybrid vehicles have problem of storage capacity, which limits driving distance. Third, production costs of hydrogen are still high and t is still at the stage of research and development. These substitutes are characterized by a unit production cost. Ryan *et al.* (2006) give detailed information on production costs as well as on rates of technological change (see Table 8). Furthermore, a capacity constraint is imposed on the availability of these technologies.

Land-based fuels are considered as imperfect substitutes for petroleum. Generally, they are mixed with petroleum to meet energy demand in transportation sector, except in Brazil where 60% of bio-ethanol production is mixed with petroleum and 40% is not. Nonetheless, other technologies such as fuel cell, electric/hybrid, natural gas are perfect substitutes or petroleum resources. Thus, energy delivered is represented as by the sum of i) a convex linear combination of petroleum and one land-based fuel and ii) a backstop. It is given by:

$$\left[\sum_{k,k\neq backstop}\theta_k^r.\left(q_k^r\right)^{\rho}\right]^{1/\rho}+q_{backstop}^r,$$

where θ_k^r is the resource k share, it is calibrated against observed data ; ρ is the elasticity of substitution taken from GTAP, it is reported in Table 9;[9] q_k^r is the <u>*endogenous*</u> input demand for resource k.

Insert about here Tables 5, 6, 7, 8 and 9.

D. International trade

To account for regional preferences, globe surface is divided into three regions according to their per capita wealth, namely high, medium and low income countries. Moreover, it is all the more important that natural resources endowment differs across geographical areas and should have important implications on international trade. For ease of simplicity and without loss of generality, we suppose that goods are perfectly homogenous[10]. Thus, quantity traded is nothing more than the difference between regional demand and regional supply. Aiming to analyze land competition between the different uses, only final food products are traded. Thus, agricultural food prices are defined at the world-wide level. Since location of petroleum resources differ from land suitability for bio-fuels production, petroleum, land-based bio-fuels and backstop technologies are exchanged. Moreover, bio-fuels policies (EU directives or USA[11]) should have important impacts on bio-fuels production in developing countries. Thus, resources prices (petroleum, land-based fuels and backstop) are defined at

5. Amount of carbon emitted in the atmosphere is not linked to the cumulated amount of resource available. This assumption may be controversial since lower is the stock level, higher is the amount of carbon emitted. For instance, carbon emitted by bituminous sands is much higher than carbon emitted by crude oil.
6. It is worth noting that results from different studies can differ dramatically.
7. The substitution possibilities between crude oil and bio-fuels are crucial.
8. If we have considered that domestic/imported goods were not perfect substitutes, we would use Armingthon elasticities.
9. According o the European directive on Renewable Resources, 5,75 percent of transportation fuels on energy basis should be provided by bio-fuels, this percentage sold reach 11 percent by 2011. Us policy for bio-fuels imposes a target on quantity produced. It states that US production should reach 28 billion litres of ethanol by 2012 and 1 billion litres of cellulosic ethanol by 2013.

the world-wide level. Transportation services are not traded, thus, prices are defined at the regional level.

E. Baseline scenario

The previous model has been calibrated over the next century in time steps of five years. It has been programmed with GAMS and solved with MINOS solver. The bulk of increase in food demands should occur over the next five decades. World food demand for processed crops products is projected to increase by 150% whereas demand for meat and dairy more than double. Annual per capita food consumption as well as dietary habits are not expected to change significantly over the next century in rich income countries. However, annual food consumption is projected to rise and the share of animal protein products is forecast to be ever-increasing medium and low income countries. Most spectacular increase should occur for energy consumption which is forecast to more than double by 2050. Nevertheless, this result hides many regional disparities. Indeed, highest rates of increase being observed in poor and medium income countries.

The largest producer of land-based fuels is the medium income region where feedstock opportunity cost is low. Representative feedstock in this region is sugar and sugar-cane which is not very demanding in land quality and has high energy conversion coefficient (Hamelinck, 2006). This region well-endowed in petroleum resources is also the largest producer of petroleum resources. Whereas medium income countries are net exporters in petroleum over the whole simulation period, they are net importers in land-based fuels except in 2005 and 2010. This latter result is well-explained by their energy choices. Land-based fuels are mixed with petroleum (25% of land-based fuels and 75% of petroleum), this share is steadily rising until 2060, date at which land-based fuels are used pure. In two other regions, land-based fuels are introduced in the energy mix (petroleum and land-based fuels) by 2015. Bio-fuels are always used with petroleum resources in poor income countries, they are used pure in rich income countries by 2055. Backstop technology becomes quite quickly used in transportation. By 2030, backstop technology is competitive with other energy sources in rich and medium income countries. It is only used in 2055 in poor income countries. All these results are described in Figures 6 and 7.

<Insert Figures 6&7 about here>

Rich income countries are net exporter in food commodities whereas two other regions are net importer. Food prices are forecast to follow a slight increasing trend until 2025, then, they are projected to diminish, but, at a lower rate than they did over the last four decades. Substantial increases in food needs combined with the land-based fuels production explain the slight increase in food prices (see Figure 5). Transportation prices are forecast to decrease over the whole simulation period.

Finally, carbon emission should be eight times higher in 2050 than current values. Then, over the next five decades, since petroleum is gradually substituting by land-based fuels and by the backstop, carbon emissions are fairly stable (see Figure 8). Nevertheless, it is worth noting that share of emissions from transportation are forecast to be ever-increasing.

Insert about here Figures 5, 6.a and 6.b, 7 and 8.

III. BIO-FUELS AND CLIMATE POLICIES

Today, share of world carbon emissions from transportation sector which amounts to 21% is the largest one. Moreover, since increase in demand for transportation is expected to be drastic for coming decades, this share should reach more than one third in 2050 (see above). Thus, regulation of emissions from transportation should be important to fight against climate change. In this section, we aim to determine how energy and climate policies impact on food and energy prices, on per capita demand for food and energy. Two types of policies have been defined.

The first one consists of defining bio-fuels mandatory blending. The U.S Energy Policy Act of 2005 mandates the production of 12 billion gallons by 2010. The European Union Directive on the Promotion of the Use of Biofuels requires that 5,75% (respectively 11%) of energy production is provided by bio-fuels in 2010 (respectively 2020). Over the last two years, the implementation of this policy in developing countries had major implications on world agricultural markets. For instance, the USA which are net exporter of maize have deviated their domestic production from exportation for food to bio-fuels, maize price has increased. Furthermore, other countries like India, Brazil plan to implement mandatory blending for land-based fuels. Nevertheless, since bio-fuels are not carbon neutral, some question arise: i) How many carbon emissions can be saved by adopting this type of policy? What could be the impact on per capita demand for food? Furthermore, what could the impact on food prices, where additional amount of land-based fuels should be produced? In order to measure the impact of mandatory blending for land-based fuels, we characterize different scenarios. As a first step, we suppose that mandatory blending for land-based fuels in rich countries are implemented, this scenario is called mandatory blending Rich Countries. Even if growth in energy demand in rich countries is the smallest one, global energy consumption in rich countries is still the largest one over the next century as well as their carbon emissions (see Figure 8). Further, as indicated by Figure 7, use of bio-fuel crops to meet energy demand is low. A mandatory minimum share of bio-fuels in total fuel consumption in the transport sector of 5% by 2010 and 10% by 2020 is set[12]. As a second step, mandatory blending is also imposed at the world-wide level, this scenario is called World mandatory blending. In this scenario, we impose a bio-fuels target share equal to 9% by 2015. Figure 6.b indicates share of bio-fuels in the energy mix (petroleum/bio-fuels) at the world-wide level. Finally, the Lagrange multiplier associated to this constraint may be interpreted as the subsidy that should be given to bio-fuels to implement this policy.

Finally, (quantity) targets are imposed on the world emissions flux and on the world carbon stock. As indicated by Figures 8, the highest level of carbon emissions should occur over the next four decades. In the scenario called emission fluxes, we impose a constraint on emission fluxes which states that carbon emission should not exceed the world carbon emissions observed in 2000/2005. Then, in the scenario called carbon stock, an upper-bound is imposed on the world stock of carbon. It is equal to 200000 billion tons of carbon (see Figure 10) .

In order to measure the impacts of the different climate policies on key variables, we systematically compare the results of the climate policies scenarios to the baseline scenario

A. Bio-fuels mandatory blending.

We first describe the results of the scenario called mandatory blending Rich Countries. According to the baseline scenario, the largest producer and consumer of bio-fuels are the Medium Income Countries. Immediate implications of the adoption of the policy are an increase in bio-fuels exports from Medium to Rich Income Countries. Since world bio-fuels production does not increase substantially, a decrease in land-based fuels consumption in Medium Income Countries is predicted. This policy is forecast to speed up petroleum extraction over the first decades. Additional petroleum extracted is consumed by Rich Income Countries and Medium Income Countries, the highest rates of increase being observed in Medium Income Countries. Furthermore, since petroleum resources are depleted earlier, the diffusion of backstop technology is more important.

This policy results in an increase in opportunity cost of land, thus, feedstock prices are expected to increase, leading to a rise in bio-fuels prices. Nevertheless, due to a slow down in Rich income Countries demand for crude oil, petroleum price decreases.

Since final transport services are not traded in this economy, transport prices are characterized at the regional level. They are expected to rise in Rich Income Countries from 2015 to 2030 since bio-fuels prices should rise. Meanwhile Medium and Poor Income Countries benefit from a decrease in transport prices since the share of energy provided by land-based fuels diminishes.

To meet bio-fuels targets in Rich Income Countries, a part of world agricultural production is deviated from food to energy crops, as a result of which, agricultural prices rise sharply from 2015 to 2030 (see Figure 5). At these dates, the constraint requires Rich Income Countries to change their energy choices towards more bio-fuels. The most significant rise is projected for the processed crop products since food and transportation compete for land. Since price elasticities for food products are very low, per capita demands are fairly affected.

Over the next century, world carbon emissions are higher than in the baseline scenario. Nonetheless, in Rich income Countries from 2015 to 2030, date at which bio-fuel policy requires Rich Income Countries to consume more land-based fuels, carbon emissions in this region diminish from the baseline case (see Figure 8). Meanwhile, carbon emissions in other regions rise due to a leakage effect. Finally, this policy is negative for climate change since carbon accumulated into the atmosphere rises sharply.

The scenario World Mandatory Blending reveals which countries are expected to “make efforts” to respect the constraint. Two questions arise: i) who will consume additional land-based fuels in order to reach world the target? ii) who will produce the additional bio-fuels? The highest rates in land-based consumption are observed in Rich and Poor Countries[13] over the first decades, decades over which backstop technologies are not competitive. The level of consumption at each period is predicted to decrease from the baseline scenario.

To reach world bio-fuels target, production of land-based is projected to increase dramatically in Medium Income Regions.

The demand for land resources goes up, thus, opportunity cost of land is projected to increase leading a

10. [12] Strictly speaking, this constraint says that the share of land-based fuels in the total energy mix (bio-fuels plus petroleum) should be greater or equal to. Figure 6.b reports the share of bio-fuels at the regional level.

11. [13] It is worth noting that land-based fuels share in energy mix were the lower in the Baseline scenario (see Figure 6).

substantial rise in bio-fuels price as well as in food prices (see Figure 5). Highest rates of increase are predicted from 2015 to 2025, dates at which the target is the most restrictive. The target is said to be restrictive at these dates since growth in world food needs is projected to be the most important, as a result land competition between agriculture and energy should be the most aggressive. Further, the noteworthy rise in food prices results in a decrease in daily consumption in Medium and Poor Countries.

Bio-fuels target is a constraint on the quantity. Since land-based demand has to increase, demand for petroleum should diminish which results in a slight slow down of crude oil.

It is worth noting that consumption of the backstop technologies does not change significantly in Rich Income Countries and Medium Income Countries and it is lower in Poor Income Countries.

Prices for transport services are expected to increase around the world when bio-fuels targets are restrictive (2015-2025) leading to a decrease in per capita demand.

Finally, the implementation of this energy policy at the world-wide level does not succeed in curbing down carbon emissions (see Figure 8).

B. Carbon Targets

Let us first analyze the results of the scenario emission flux. As highlighted by Figure 8, this constraint is only restrictive over the first four decades. Regional effects of this policy are different (see Figure 9). More efforts will be made in region where the marginal cost of reducing carbon emissions is the lowest. As pointed out by Figure 9, Rich and Medium Income Countries are projected to reduce their carbon emissions from the baseline scenario whereas Poor Income Countries are predicted to increase their carbon emissions. Then, inside each regions, let us isolate the least costly strategy to meet flux targets. In order to reduce their carbon emissions, petroleum consumption in Rich Income Countries diminishes from the baseline scenario. Meanwhile, backstop technologies are adopted earlier and their rates of diffusion are higher than in the baseline scenario. As a result, transport services prices is projected to rise, leading to a decrease in per capita demand for energy in Rich Income Regions from 2005 to 2030, dates at which the constraint is restrictive. Medium Income Countries are projected to postpone their consumption of crude oil over the first decades. A rise in transport prices drives down per capita demand for energy in this region. Finally, it is worth noting that this policy does not impact on world agricultural sector since the rise in land-based consumption is a too costly strategy to meet the target.

Let us now analyze the results of the scenario carbon stock. In order to reach this constraint, the three regions adopt the same strategy (see Figure 10). They diminish their consumption of polluting energy sources: petroleum and land-based fuels. Nevertheless, it is worth noting that rates of decrease are higher for bio-fuels production. Backstop technologies are adopted earlier and their rates of diffusion are higher than in the baseline scenario. Further, energy prices are expected to increase, thus, per capita demand in each region is projected to decrease. Since bio-fuels production is expected to decrease, lands are deviate from energy crop production to agricultural production, thus, competition for land resources is less aggressive and opportunity cost of land diminish as well as food prices.

Insert about here Figures 9 and 10.

IV. SENSITIVITY ANALYSIS

A. Technology Parameters

Two kinds of sensitivity scenarios have been characterized. Firstly, the timing of adoption of land-based fuels depends upon the relative cost of backstop technology with feedstock and petroleum. In the baseline scenario, backstop technology is adopted quite early in Rich and Medium Income Countries. Nonetheless, backstop production cost may differ across studies. In the baseline scenario, backstop production cost was extracted from Hamelinck's study (2006) and is quite low comparatively to other studies. Thus, a higher production cost is defined in the scenario, called backstop cost[14]. Besides the production cost of the backstop, a parameter also affects the development of land-based fuels, which is the capacity constraint on the backstop. For instance, hybrid vehicles have problem of storage capacity, which limits driving distance. Capacity constraint defined in the baseline scenario was quite optimistic about the rate of diffusion of these technologies. Thus, in this scenario called backstop capacity, we suppose that the capacity constraint is more drastic. Secondly, the elasticity of substitution between fossil fuels and feedstock in transportation is crucial. Nonetheless, this value is highly uncertain (Birur et al., 2007). In the baseline scenario, elasticities of substitution were close to one meaning that technology gives the opportunity to change quite "easily" the energy mix (crude oil/land-based fuels) when the relative price changes. Nevertheless, technological barriers still exist. For instance, bio-ethanol and bio-diesel can not be used pure in most

12. [14] This production cost is supposed to increase by 35%.

vehicles. Thus, to explore in what extend these technological constraints can prevent from the diffusion of land-based fuels, we build a scenario where the elasticity of substitution is lower (see Table 9), this scenario is called elasticity of substitution.

Backstop Cost. In each region, the date at which the backstop is expected to become competitive is postponed by around 5 years. Further, the diffusion of this technology is slowed down around the globe. Consequently, to meet future energy needs, demands for petroleum and land-based fuels are expected to rise. Petroleum is becoming scarcer, as a result of which, its price is expected to fairly rise over the next century. Meanwhile, induced demand for land lead to an increase in opportunity cost of land resources driving up land-based fuels prices. Nevertheless, since the relative price crude oil/land-based fuels should change in favour of land based fuels, energy mix: petroleum/land-based fuels should change towards more land-based fuels. Whereas this change is fairly significant in Rich and Medium Income Countries, it is very slight in Poor Income Countries.

Following a rise in energy sources prices (crude oil, land-based fuels and backstop), prices for transportation is expected to rise, the increase being more important in Rich and Medium Income Countries. As a result, per capita consumption of energy diminishes in all regions over the next century[15].

Increase in world food prices from the baseline scenario is under 5%, thus, per capita food demand is not affected (see Figure 11).

World carbon emissions are expected to diminish from the baseline scenario over the first decades (see Figure 12). Whereas carbon emissions are expected to reach more than one third in the baseline scenario, they should not exceed one quarter at this date in this scenario.

Backstop Capacity. The effects are similar to the previous one. Maybe, the best way to present is to show the results with figures 11 and 12.

Elasticity of substitution. The decrease in the elasticity of substitution means implicitly that some technological constraints may prevent the substitution between crude oil and land-based fuels induced by a change in relative price. A decrease in the elasticity of substitution induces a slow down in factors prices: crude oil and land-based fuels. Nevertheless, this slow down is more important for petroleum, it is quite insignificant for land-based fuels. Thus, price for petroleum decreases more than for land-based fuels, world extraction of crude oil is speeded up over the first decades (from the baseline scenario), thus petroleum resources are depleted earlier. World demand for land-based fuels is slowed down. The decrease of the elasticity speeds up the adoption of the backstop technology and increases its rate of diffusion at the world-wide level. In Rich and Medium Income Countries, the backstop is adopted 15 years earlier than in the baseline scenario.

Due to a substantial rise in transportation services prices, per capita demand for energy around the globe should decrease from the baseline scenario. Over the first decades (until 2015), demand for crude oil and land-based fuels is higher than in the baseline scenario in Rich Income Countries. Whereas demand for crude oil is higher in Medium Income Countries until 2015, over the next century, land-based fuels consumption in Medium Income Countries is systematically lower than in the baseline scenario.

World demand for land-based fuels diminishes driving down the demand for land resources as a result food prices should decrease from the baseline scenario. Further, they should follow a decreasing trend (see Figure 11).

Since demand for petroleum is stimulated over the first decades and despite the decrease in per capita demand around the globe, carbon emissions should increase significantly over this period (see Figure 12). Then, thanks to the adoption of the backstop which substitutes for crude oil and land-based fuels, carbon emissions are significantly curbed down and are lower than in the baseline scenario. It is worth noting that it is positive for climate change since carbon accumulated into the atmosphere is lower than in the baseline scenario from 2025.

Insert about here Figures 11 and 12.

B. Marginal Lands

In previous scenarios, agricultural area is supposed to be constant. Nevertheless, it may be efficient to convert marginal lands or forest lands into agricultural uses to meet food and land-based fuels when food prices rises. Last year, the increased demand in oil-palm had speeded up the rate of deforestation in Indonesia.

We introduce in the model a stock of marginal land which can be converted into agricultural use and it is denoted by $ML_{i,r}$. This stock of land embodies marginal and forest lands which are classified as suitable for agricultural production (Wiebe, 2004). Since the most accessible lands will be put into cultivation first, conversion cost is supposed to be increasing with the area of land converted and it is

13. [15] Obviously, the decrease in per capita consumption is a decreasing function of the price. Thus, it is more important in Rich and Medium Income Countries.

given by the following equation: $cc_{i,r,t} + \left(\sum_t ml_{i,r,t} \right)^2$.

Further, since marginal lands are used by the forest sector to produce wood products, an exogenous rent is associated to each marginal lands.

At each period, some marginal lands may be converted into agricultural uses. Thus, land available for agriculture is considered as a dynamic stock which is given by the following equation:

$$Land_{i,r,t+1} = Land_{i,r,t} + ml_{i,r,t}$$

Where $Land_{i,r,t}$ is land available for agricultural production at date t, $ml_{i,r,t}$ is the marginal or forest land converted into agricultural use at date *t*. Meanwhile, the dynamic of the stock of marginal is given by:

$$ML_{i,r,t+1} = ML_{i,r,t} + ml_{i,r,t}$$

Further, area converted to agricultural uses has to respect the following inequality: $ml_{i,r,t} \leq ML_{i,r,t}$ at each period. Finally, land area constraint may be written in the following way:

$$\sum_u L_{i,u,t} \leq Land_{i,r,t}$$

The multiplier of this constraint is the shadow price of land class *i* allocated to use *u*.

Marginal lands are mainly converted in Rich and Medium Income Countries over the first decades. Indeed, over the first decades, the increase in food needs should the highest and the need for land-based should be important since the backstop technology is not competitive.

Additional lands are mainly allocated to extensive grazing system. Thus, croplands which were previously used for agricultural uses are now allocated to energy crops. Bio-fuels production is expected to increase significantly; as a result, the share of land-based fuels in the energy mix (petroleum/bio-fuels) is expected to rise significantly in Rich and Medium Income Countries[16]. Consequently, world carbon emissions from transportation should diminish significantly. Nevertheless, emissions induced by the conversion of marginal lands into agricultural lands are not taken into account.

World resources prices (petroleum, land-based fuels and backstop technology) should slightly diminish but this decrease is not significant. Regional transport prices should not change as well as per demand for energy.

Thanks to the conversion of marginal lands, land competition between agriculture and energy is less aggressive. Indeed, world land-based fuels production may increase without hurting world agricultural markets. Rise in land-based fuels production does not impact on agricultural lands shadow prices, thus, food prices are not affected. World agricultural production should not benefit from the conversion of marginal lands as a result per capita demand for food products should not change significantly from the baseline scenario.

V. CONCLUSIONS

A model of world land allocation combined with an Hotelling model have been developed in this paper in order to analyze the production potential of land-based bio-fuels as well as their potential role in climate policy. Further, the model tracks the feedback effects of energy and climate policies on the world agricultural sector. First, effects of energy and climate policies are analyzed. Bio-fuels mandatory blending should have negative effects on the world agricultural sector since they induce substantial rises in food prices and decreases in per capita demand for food, especially in poor income countries. Meanwhile this policy is not positive in terms of climate policy. Then, carbon targets have been introduced in the model. Results reveal that the development of land-based fuels is not the least cost strategy to meet the targets. Second, sensitivity with respect to technological parameters and availability of marginal lands has been run.

The model may benefit from different extensions. First, results of the different scenarios highlight an increasing trend in food prices or at the very least, a slow down in the rate of decrease of food prices. Over the last decades, a slow down has been observed in the level of investment in R&D in agriculture. Thus, it would be interesting to define the level of agricultural productivity as a function of food prices. Higher are the food prices, higher is the investment in R&D, higher is the agricultural productivity. Second, most countries impose several forms of trade restrictions on both feedstock and biofuels, with preferential waivers of tariffs and quotas for certain countries. Modelling the impacts of global trade in biofuels for the environment and especially for climate would be a topical area of future research.

14. [16] Energy choices should not be affected in Poor Income Countries.

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