Unravelling land-use change mechanisms at global and regional scales

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Abstract

Unravelling the dynamics of land-use change is key to assess the environmental and socio-economic impacts of land-based strategies regarding climate or energy. In this prospect, this paper proposes an analytical decomposition of land-use change resulting from a shock in agricultural demand which takes into account indirect effects from price signals. This analytical equation is numerically estimated using a global model of land-use combining biophysics and economics. While being relatively simple, this model captures the main processes of land-use change: change in the intensive and extensive margins, international trade, change in intermediary demand and possible by-products. At the global scale, our results show that yield losses due to the conversion of marginal land amount approximately to half of yield gains due to fertiliser use. At the regional scale, patterns of yield and area responses are depicted by assessing the potentials for intensification (yield gaps) and extensification (areas of extensive pastures) given the future pathways of agricultural demand.

Keywords: Land-use change, Biophysical economics, Energy transition

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1 Introduction

The debates on the environmental impact of producing biofuel emphasises the complex nature of land-use dynamics as it puts into play responses from the demand and supply-side, based on price signals and biophysical potentials. Every change in agricultural production leads to price change inducing mechanisms of intensification, reallocation of production and changes in demand. This price-induced effect is usually referred to as indirect land-use change (ILUC). This concept has been used mainly within the debate on the environmental impact of biofuel, even though it concerns every type of change in the agricultural system which may affect the price vectors (e.g., reduction of agricultural area, change in diet). ILUC has been estimated by many studies (Searchinger et al., 2008; Debucquet, 2011; Havlík et al., 2011; Valin et al., 2015), and there is now a consensus about its importance in the environmental assessment of biomass products.

Yet, mechanisms underpinning some aspects of land-use change (LUC) at global and regional scales remain unclear for some aspects. LUC estimates are generally presented as aggregate figures, without detailing the individual processes from which they result. Thus, identical estimates of LUC could be obtained from different logical paths. Melillo et al. (2009) made a first step towards more detailed estimates by explicitly distinguishing direct and indirect land-use change, showing that the latter could be responsible for substantially more carbon loss than the former. Hertel et al. (2010) tackled this issue by decomposing global LUC from a change in maize-ethanol production in the US as the sum of market-mediated responses and by-product use. This work is an important step towards a better understanding of LUC mechanisms, but has left grey areas in some important aspects. As Hertel himself admitted, the modelling of the "extensive margin" – i.e., the reduction in average yield as less productive lands are brought into cultivation – is rather simplistic in his study, because it employs a quite ad hoc substitution elasticity of 0.66 between additional and current cropland areas at global scale (meaning that on average, productivity of new lands is about two-thirds of the average productivity of existing croplands). Based on a more sophisticated modelling associating an ecosystem model, Taheripour et al. (2012) obtained estimates of the extensive margin generally higher than Hertel et al. (2010), with, e.g., factor ranging from 0.89 to 1 for Brazil. However, these estimates do not correctly take into account possible substitution constraints due to crop-livestock relations. In particular, pasture used in the intensive system are complementary inputs of cropland and cannot be considered as substitutable to them. In addition, these estimates have never been included to our knowledge in a land-use change decomposition in the manner of Hertel et al. (2010). Other references to the extensive margin topic can also be found in Keeney and Hertel (2009) and Hertel (2011).

The knowledge gap about the underlying mechanisms of land-use change is a major impediment to produce relevant projections of intensification/extensification patterns at global or regional scales. This is evidenced by the large discrepancies on the relative yield-area response in model intercomparison assessments (Nelson et al., 2014). To improve our understanding of land-use dynamics, the objective of this paper is to provide a land-use change decomposition in the manner of Hertel et al. (2010), but with refinements on some aspects. E.g., the substitution elasticity between additional and current cropland areas is not exogenously fixed as in Hertel et al. (2010) or Taheripour et al. (2012), but evolved dynamically over the simulation, reflecting the fact that marginal land becomes on average less and less suited for crop production. Most importantly, we take into account crop-livestock interactions and their implication for the substituability between pasture and cropland areas. By doing so, we intend to provide insights on some key questions to project future land-use change: how yields change through input use? How expanding on marginal lands affect mean yields? How production is reallocated over the world regions? We first provide an analytical decomposition of land-use changes from an external shock in agricultural demand. This decomposition distinguishes land-use changes resulting from the production shock from those which result from price-induced effects. The market-mediated effects considered are: (i) changes in yield due to input use and to expansion on marginal lands; (ii) changes in the production allocation among countries and sectors (crop and livestock); and (iii) changes in final demand. We then undertake a numerical analysis using the Nexus Land-Use (NLU) model (see Souty et al. (2012) and Section 3.1.1), which is a global partial equilibrium model of land-use combining biophysics and economics, for a scenario of biofuel scenario produced from rapeseed in Europe. The sensitivity of the dynamics of extensification and the potential of intensification is also assessed by testing a range of key model parameters.

2 Analytical decomposition of land-use change

Demand or supply shocks induce a complex mechanism of producers' and consumers' decisions driven by changes in price signals. Following Hertel et al. (2010), price-induced effects on land-use can be summarized as follows: (i) reallocation of production among countries (through international trade) and agricultural sectors (substitution among crops, substitution between grass and crop to feed livestock); (ii) crop yield changes resulting from the combined effect of the intensive margin (mainly from changes in use of inputs) and the extensive margin (referring to the reduction in average yield as less productive lands are brought into cultivation); (iii) changes in final biomass demand (see Fig. 1). The arrow between the "Demand/supply shock" box and the "Reallocation of production" box refers to the by-products effect. Note that each component of this scheme may feedback to influence another through the price channel. Arrows depicting possible feedback effects are not shown for clarity.

The conceptual framework shown in Fig. 1 can be translated into analytical terms based on the simple relationship between land-use change ΔA_i for a crop i in the set of crops C, baseline production Q_i^B and yield Y_i^B (which include change already happening), and final production Q_i^F and yield Y_i^F after a shock Q_i^S:

$$\forall i \in C:$$
$$Y^i = A^i \times Q^i \tag{1}$$
$$\Delta A_i = \frac{Q_i^F}{Y_i^F} - \frac{Q_i^B}{Y_i^B} \tag{2}$$

By adding and subtracting $\frac{Q_i^F}{Y_i^B}$, Eq. 2 can be decomposed as follows:

$$\Delta A_i = \frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B} + \frac{Q_i^F}{Y_i^B} - \frac{Q_i^B}{Y_i^B} \tag{3}$$

With $\frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B}$ and $\frac{Q_i^F}{Y_i^B} - \frac{Q_i^B}{Y_i^B}$ corresponding to the land-use changes due to the changes in yield and to the changes in production, respectively.

Defining $\Delta Y_i^{\Delta p_c}$ as the change in yield of crop i due to a change in price of crop c, by adding and substracting $\frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}}$, we get the following expression:

$$\Delta A_i = \frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} + \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} - \frac{Q_i^F}{Y_i^B} + \frac{Q_i^F}{Y_i^B} - \frac{Q_i^B}{Y_i^B} \tag{4}$$

If Q_i^F is defined as:

$$\forall i \in C: \quad Q_i^F = Q_i^B - Q_i^{By} + \mathbb{1}_{i=c} Q_i^S + \Delta Q_i^D + \Delta Q_i^T + \Delta Q_i^{ID} \tag{5}$$

Where:

Q_i^{By} = Byproducts production that can replace the crop i
ΔQ_i^D = Change in production of crop i due to changes in final demand of crop i
ΔQ_i^T = Change in production of crop i due to changes in international trade of crop i
ΔQ_i^{ID} = Change in production of crop i due to changes in intermediate demand of crop i
$\mathbb{1}_{i=c}$ is equal to 1 if i =c, to 0 otherwise

Let us replace Q^F by its expression given in Eq. 5 in $\frac{Q_i^F}{Y_i^B}$:

$$\begin{aligned}\Delta A_i = {} & \frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} + \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} - \frac{Q_i^F}{Y_i^B} + \\ & \frac{Q_i^B + \mathbb{1}_{i=c} Q_i^S + Q_i^{By} + \Delta Q_i^D + \Delta Q_i^T + \Delta Q_i^{ID}}{Y_i^B} - \frac{Q_i^B}{Y_i^B}\end{aligned} \tag{6}$$

which gives:

$$\begin{aligned}\Delta A_i = {} & \mathbb{1}_{i=c} \frac{Q_i^S}{Y_i^B} + \frac{Q_i^{By}}{Y_i^B} + \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} - \frac{Q_i^F}{Y_i^B} + \frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} + \\ & \frac{\Delta Q_i^T + \Delta Q_i^{ID} + \Delta Q_i^D}{Y_i^B}\end{aligned} \tag{7}$$

In Eq. 7, $\frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}} - \frac{Q_i^F}{Y_i^B}$ refers to the land-use changes due to the changes in crop yield from the intensive margin (input use). $\frac{Q_i^F}{Y_i^F} - \frac{Q_i^F}{Y_i^B + \Delta Y_i^{\Delta p_c}}$ corresponds to the land-use change due to changes in crop yield from the extensive margin (marginal lands). $\frac{\Delta Q_i^T + \Delta Q_i^{ID} + \Delta Q_i^D}{Y_i^B}$ refers to the land-use changes due to changes in trade balance ΔQ_i^T, changes in intermediary demand ΔQ_i^{ID} and changes in final demand ΔQ_i^D. These three effects are market-mediated effects resulting from the changes in prices, contrary to $\mathbb{1}_{i=c} \frac{Q_i^S}{Y_i^B} + \frac{Q_i^{By}}{Y_i^B}$ which corresponds to the land-use changes due to the production shock and its possible by-products.

3 Numerical estimation

3.1 Material and method

3.1.1 NLU short description

The analytical decomposition of land-use change displayed on Eq. 7 is numerically estimated using the NLU model. NLU is a partial equilibrium model in which the agricultural sector is divided into 12 regions of the world, inter-connected with each other by international trade. This model belongs to the family of economic models which provide a more detailed representation of market mechanisms than geographic models (see e.g., Hall et al., 1995; Žiga Malek et al., 2018; Ke et al., 2018), at the expense of a coarser modelling of local land-use dynamics (e.g., neighborhood or stratification effects). Economic models are for this reason particularly adapted to regional to global scales, while geographic models are mostly applied to local to regional scales (Heistermann et al., 2006).

NLU provides a simple representation of the main processes of agricultural intensification for crop and livestock production: the substitution between (i) land and fertiliser for the crop sector and (ii) grass, food crops, residues and fodder for the livestock sector. It does so by minimising the total production cost under a supply-use equilibirum on food and bioenergy markets. A detailed description can be found in Souty et al. (2012) or in Brunelle et al. (2015). Main model equations are also given in SI. We sum up in this section some key features for a better understanding of the following results.

NLU allows two types of land-use: cropland and pastures. Forested areas are assumed to be controlled by external scenarios and therefore not endogenously modelled. Three categories of pasture are distinguished: intensive, extensive and residual pastures. Cropland area can only expand to extensive and residual pastures, and no direct conversion from forest to cropland is possible. Consistently with Bouwman et al. (2005), intensive pasture are considered to be complementary inputs of cropland, as they produce grass in complement to food crop to feed animals. The balance of supply and demand of food crop products is established on the basis of data from the global database Agribiom (Dorin and Le Cotty, 2011). This database provides, for each country, the biomass balances in kilocalories based on the FAO annual country-level supply-utilisation accounts, ensuring consistency among the annual flows of edible biomass which are produced, traded, and consumed.

Two categories of crops are distinguished in NLU: “dynamic” crops, corresponding to most annual crops (cereals, oilseeds, sugar beet and cassava), and “other" crops corresponding mostly to perennial crops (e.g., sugar cane, palm oil and some fodder crops). All categories of crops are aggregated based on their calorific values. Considering crop aggregates rather than modelling separately each crop type makes it possible to simply represent rotation constraints. Cropping intensity is assumed to be constant over the simulation period. The evolution of cultivated areas and yields for “other" crops are determined exogenously. On the other hand, “dynamic" crop yields are endogenously determined, taking into account biophysical constraints and the amount of fertilizer used. For 2001 (model base year), total cropland area amounts to 1472 Mha at global scale, divided between 748 Mha of “dynamic" crops and 724 Mha of “other" crops. Production on “dynamic" cropland represents 87% of the global calorie production.

The intensive margin is modelled with a non-linear response of yield to fertiliser inputs.

The asymptote of this function corresponds to the potential crop yield given by the vegetation model LPJmL (Bondeau et al., 2007). The minimum yield and the slope at the origin are calibrated so as to minimise the model error between historical and modelled yields area over the period 1961-2006. The fertilizer price is calculated based on energy prices (oil and gas) following an econometric method detailed in Brunelle et al. (2015).

Modelling the dynamic of the extensive margin is particularly challenging as it requires information on the conversion costs which are difficult to obtain at the global scale. To circumvent this problem, we represent the extensive margin using regional land distributions of potential yields[1]. These distributions are calculated by mapping the land-use dataset from Ramankutty et al. (2008) on the potential yields from the vegetation model LPJmL (see Souty et al. (2012) and SI for more details). They are used to model a Ricardian production frontier splitting agricultural lands into two parts: an intensive system, composed of a mosaic of crops and pastures, and an extensive system, exclusively composed of pastures. The expansion of one system on to another depends on their relative profitability: the intensive system uses relatively less land and more fertiliser input than the extensive one, it is thus at an advantage when the land price rises or the fertiliser price falls. The base year data shows that a fraction of extensive production remains in the intensive livestock production system. This residual pasture production highlights a failing in our theoretical modelling framework, that prevents us from making a clear division between the intensive and extensive systems. These deviations can be related to geographic constraints such as accessibility issues, or to institutional features related to laws on land property rights. In NLU, this type of pasture, called “residual”, can be converted to the intensive system given a parameter, labelled “accessibility parameter" in the remainder of the paper, calibrated so as to minimise the model error between historical and modelled cropland area over the period 1961-2006.

International trade is modelled by using a pooled representation without any consideration of the geographical origin of goods. Imports and exports are determined based on relative regional calorie prices (see Souty et al. (2012) for more details).

An evaluation of the model performances over 1961-2001 is provided by Souty et al. (2013).

3.1.2 Regional estimates of the extensive margin

The reduction in average yield as less productive lands are brought into cultivation, usually referred as the “extensive margin" is sometimes modelled in quite ad hoc manner while this parameter can have a large influence on the projected land-use change.

Following Taheripour et al. (2012), the mean value of the extensive margin (i.e., substitution elasticity between additional and current cropland areas) in a given region can be calculated as the ratio of mean potential yields on extensive pasture and on cropland. In NLU, the extensive margin is endogenously modelled using regional land distributions of potential yields. To compare our results with the estimates obtained by Taheripour et al. (2012), we use land-use data from Ramankutty et al. (2008) and potential yields data from

[1] Potential yield corresponds to climatic potential yields taken as a mean of five LPJmL simulation years between 1999 and 2003 in order to minimise the climatic bias due to interannual variability. Potential yields are approximated via 3 parameters (i) the maximum leaf area index potentially achievable by the crops (ii) a scaling factor between leaf-level photosynthesis and stand-level photosynthesis, and (iii) the harvest index

LPJmL. Estimates of potential yields are detailed in (Bondeau et al., 2007) and Souty et al. (2012). In addition, we use data from Bouwman et al. (2005) to distinguish between intensive and extensive pastures. To reflect the bottom-up processes of livestock production, we consider, consistently with Bouwman et al. (2005), that only extensive pastures can be converted into cropland, while conversion of intensive pastures, which are complementary inputs of cropland as they produce grass in complement to food crop to feed animals, is not feasible. Obtained values for the 12 model regions are reported in Table 1 and compared with ranges of estimates from Taheripour et al. (2012) (see region map in SI).

Table 1 shows that the estimates used in NLU are often well below the range given by Taheripour et al. (2012). They are also generally lower than the parameter used by Hertel et al. (2010) (0.66). The use of different datasets of land-use and potential yields is a first source of discrepancies. Indeed, there are substantial variations in global land cover maps (Fritz et al., 2011), as well as in potential yields and net primary productivity estimates. An other significant source of discrepancies originates from the asumption that intensive pastures cannot be converted into cropland. Following Bouwman et al. (2005), these pastures are located in mosaic with cropland, thus rather on the most productive lands. Depending on the regions, and their more or less intensive pattern of livestock production, preventing the conversion of intensive pasture into croplands amounts to removing a significant fraction of highly productive pastures from the equation, which mitigates substantially the extensive margin. By comparing the second and third column of Table 1, we see that excluding the intensive pastures reduces the extensive margin by up to -45% in China.

3.1.3 Sensitivity of results to key model parameters

Among the different market-mediated effects resulting from an external shock on the agricultural system, the response in crop yield is considered as the most uncertain (Gohin, 2014). To have a better view on the role of the response in crop yield, we performed a sensitivity test by varying the values of two model parameters: (i) the slope at the origin of the yield-fertiliser function; and (ii) the accessibility parameter governing the availability of extensive pasture for crop production. We emphasise that we calculated here a sensitivity, not an uncertainty, because we cannot associate the range on which the sensitivity test is performed with any probability distribution. Our best guess corresponds to the default model calibration.

The sensitivity in the first parameter highlights the influence of the intensive margin. The slope at the origin of the yield-fertiliser function drives the cost of increasing crop yields: the lower the slope, the greater the cost of increasing yields. While there is some consensus on the form of the function, there is no agreement regarding the current position of world agriculture on this curve. To map a part of this divergence, we used two calibrations of the yield-fertiliser function. The first one corresponds to the NLU default case, which is rather pessimistic (i.e., a number of world regions are already relatively close to the asymptote). In the second variant, the yield-fertiliser function is calibrated to reproduce approximately the aggregate crop yields and fertiliser consumption given for 2050 given by the 2012 FAO projections of Alexandratos and Bruinsma (2012). This second case is seen as rather optimistic (i.e., regions are relatively further from the asymptote). Regional slopes at the origin in 2050 in both variants are shown in Supplementary Information.

The sensitivity on the accessibility parameter of residual pastures (i.e., extensive pas-

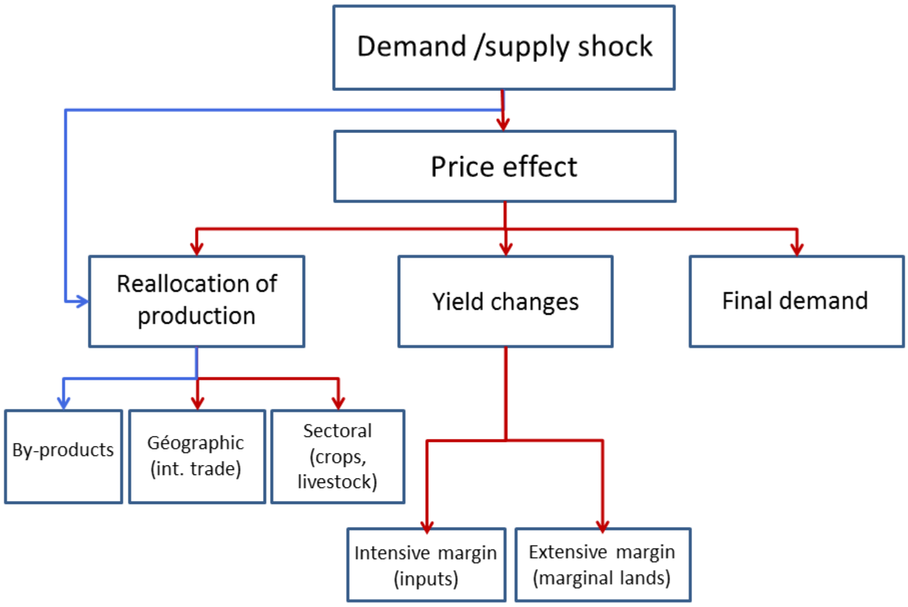

Figure 1: Price-induced effects (and possible by-products) from an external demand/supply shock

Table 1: Estimates of the substitution elasticity between additional and current cropland areas (extensive margin) at model base year based on land-use data from Ramankutty et al. (2008) and potential yields data from LPJmL excluding (column 2) and including (column 3) intensive pastures, and comparison with ranges of estimates from Taheripour et al. (2012)

	Estimates NLU	Estimates NLU incl. intensive pasture	Range of estimates from Taheripour et al. (2012)
USA	0.31	0.43	0.51 - 1
Canada	0.99	0.99	0.94 - 1
Europe	0.63	0.93	0.83 - 1
OECD Pacific	0.29	0.35	0.65 - 1
Former Soviet Union	0.57	0.58	0.46 - 1
China	0.16	0.28	0.80 - 1
India	0.49	0.63	0.71 - 1
Brasil	0.81	0.82	0.88 - 1
Africa	0.56	0.59	0.77 - 1
Rest of Asia	0.30	0.36	0.43 - 1
Rest of Latin America	0.59	0.63	0.59 - 1

tures located on best lands) provides the error on the extensive margin. In the first model run, the parameter was fixed at their calibration value; then, it was progressively relaxed. In NLU, the annual conversion rate of the residual pasture into intensive pasture/cropland is linearly related with the pressure on land (approximated by the land rent) up to a maximum of 1% based on benchmark simulations over 1961-2006 (see Souty et al. (2013) for more details). For our sensitivity test, we increase this maximum to 5%, 10% and 20%[2]. Overall five variants have been tested (fixed, 1%, 5%, 10% and 20%).

3.1.4 Scenario

In this paper, we estimate the analytical decomposition of land-use change by simulating a supply shock. This shock corresponds to a yearly demand for first generation biodiesel energy to be produced by winter oilseed rape (WOSR) increasing linearly from 2001 to 2030 to reach 4 Mega tons oil equivalent (Mtoe) per year of biodiesel (160 PetaJoules). The shock in production is assumed to take place entirely in Europe. Thus, Europe may import crops which have been substitued by WOSR for biofuel, but is assumed not to produce biofuel with imported WOSR. This additional production is implicitly assumed to result from public subsidies, however no assumption is done about the type of it (tax credit, mandate or others) and no associated financial flux is represented in this partial equilibrium framework.

The purpose of this scenario is not to provide another estimation of ILUC from first generation biofuel. The WOSR scenario has been chosen as it is a rather standard one and is easily comparable with estimates available in the academic literature.

A reference scenario was implemented based on the food consumption per capita, population, energy price and deforestation rate reflecting the Shared Socioeconomic Pathway 2 (SSP2) developed for the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5). SSP2 corresponds to a middle of the road scenario O'Neill et al. (2014). As an example, the food scenario used in this study is based on the projections provided by Alexandratos and Bruinsma (2012) and deforestation rates follow the trends observed over 2001-2010.

As NLU includes only two representative crops for each region, the model was adapted to simulate the effects of a demand shock for a single product (biodiesel from WOSR) on model outputs. The new version of the model thus includes a specific crop in addition to the representative crops already defined.

Since we focus on WOSR produced in Europe, the land classes involved in WOSR production were identified on the basis of the overall energy yields achieved by crop rotations that include this crop. Crop yields are derived from the LPJmL global ecosystem model, and the yields of the crop rotations including WOSR were derived from the French official statistics agency, Agreste. For simplicity, we assumed only one crop rotation (WOSR - wheat - barley) in Europe, which is the most common. A distribution of current areas dedicated to producing this specific crop on the identified land classes was subsequently set up. When a demand for biodiesel exists, the expansion of its area follows this distribution and takes place on "dynamic" croplands.

[2] In our experience of modelling, 20% is the value beyond which results become much less sensitive to an increase in the maximum conversion rate.

The demand for WOSR was forced by exogenous scenarios (4 Mtoe to 2030, see *infra*). Food produced in the rotation (wheat and barley) was used to meet food demand, while the quantities of co-products produced with WOSR (i.e. WOSR meal) were added to the livestock feed pools based on their energy content.

Let us note that the assumption made in this section concerns only the WOSR production. The representative aggregate of annual crops described in section 3.1.1 is characterised by its own rotation constraints and delivers its own quantities of co-products.

3.2 Results

Results are presented both at the global and regional scales. We display first the general principles at the global scale before detailing the regional results.

3.2.1 Global scale

Total land-use change (LUC) relative to the reference scenario is shown on Fig. 2. This figure corresponds to the evaluation of Eq. 2. Total LUC reaches 1730 kha (170-2980) in 2030 at the global scale. Our central estimate corresponds to an LUC factor of ~430 kha per Mtoe produced. This figure is in line with the results of Debucquet (2011) for rapeseed and slightly lower than Valin et al. (2015). The price impact relative to the reference amounts to +1.1% in 2030 at the global scale.

We performed an analysis of variance (two-ways non repeated ANOVA) to estimate the contribution of each tested parameter to the error. As a reminder, we tested two variants for the slope at the origin of the yield-fertiliser and five variants on the accessibility parameter (see Section 3.1.3). As shown in Table 2, 2% of the total variance is explained by our variants on the yield-fertiliser function and 92% by our variants on the accessibility parameter. This result is not surprising as we have much less information on the dynamic of crop expansion (in terms of conversion costs or historial datasets) than on intensification patterns. Interactions between both parameters is included in the residual and account for less than 6% (its exact value cannot be calculated as we have non-repeated measures).

Figure 3 corresponds to the numerical evaluation of Eq. 3. It shows that net LUC results from 3800 kha of additional land due to the production changes partially offset by 2000 kha of spared lands due to yield changes. The mechanism of LUC due to yield change is presented in Fig. 4. LUC due to yield change results from a land gain of 3900 kha due to higher fertiliser use, reduced by 1850 kha because of the lower productivity of newly converted cropland. On this point, our study is more optimistic than that of Hertel et al., who found that the increase in yields due to higher prices, and hence higher fertiliser use, is almost completely balanced out by the lower productivity of the marginal land that has been brought into use.

The functioning of LUC resulting from production change is more complex (see Fig. 5). The initial shock in WOSR production entails a need for land of ~4100 kha. WOSR meal replacing the use of crops to feed animals reduces this amount of land by ~1500 kha. International trade plays a significant role in the net LUC at global scale even if the balance of trade remains equilibrated as in the reference scenario. The reallocation of production to regions with lower crop yields leads to an increase in land use of ~700 kha. International trade should, however, not be understood as having an adverse effect on LUC, as reallocat-

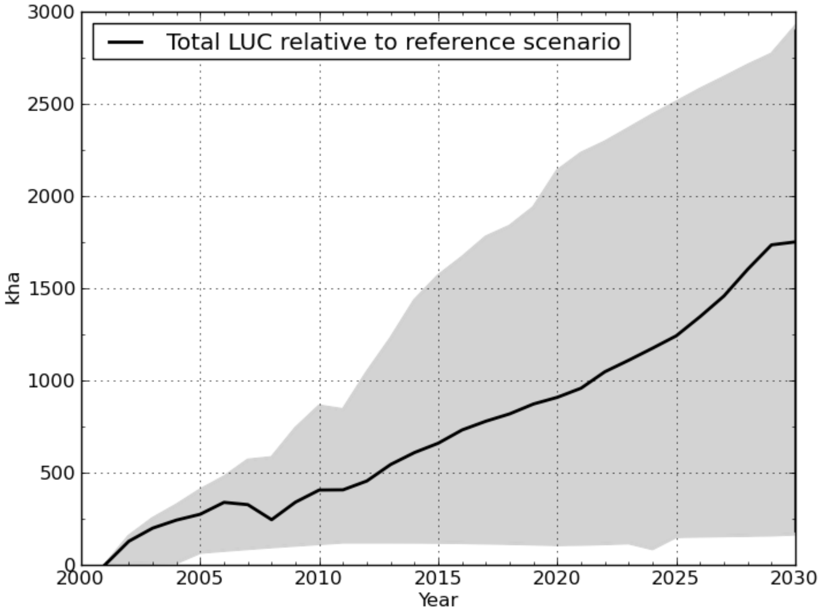

Figure 2: Global net land-use change due to the biofuel production shock: NLU default run (solid line) and range of the sensitivity tests (grey shaded area).

Table 2: Two-ways non repeated analysis of variance

	Sum of squares	Degree of Freedom	Mean squares	F	p-value
Yield-fertiliser function	196 560	1	196 560	4.62	0.0509
Accessibility	8 801 220	4	2 200 305	51.73	7 E-9
Residual	552 878	13	42529		

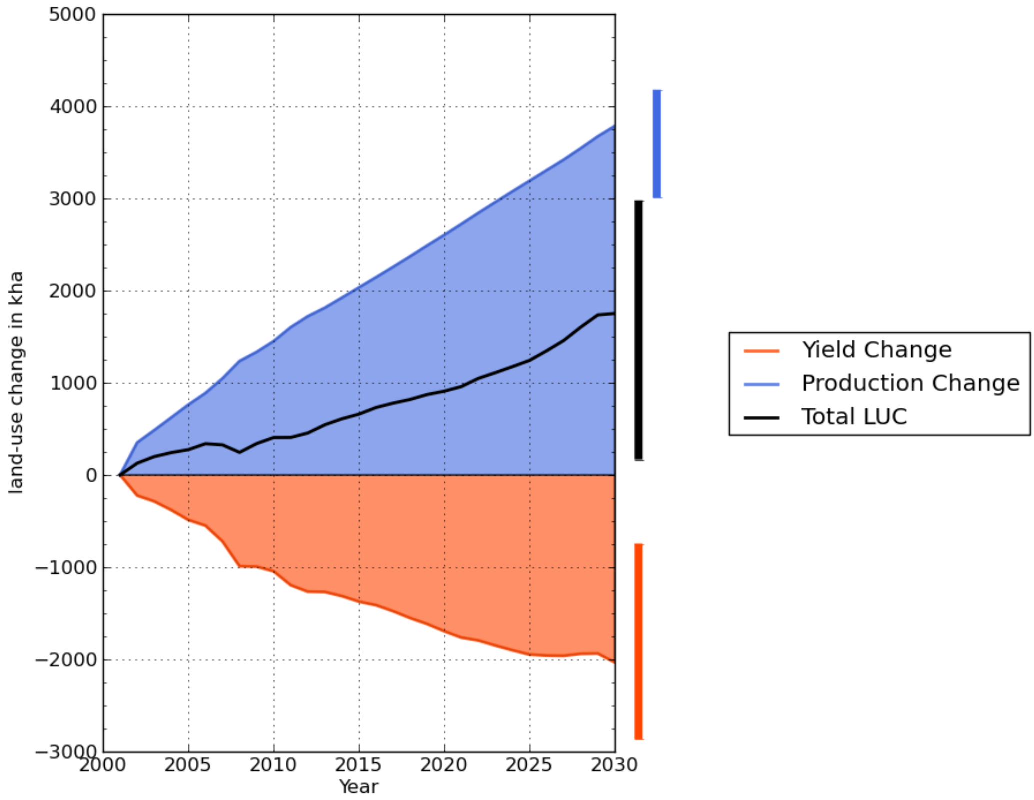

Figure 3: Decomposition of global net LUC (black line) due to the biofuel production shock distinguishing LUC from production change and LUC from yield change. Following Eq. 3, net LUC is the sum of LUC from production change (corrected from yield change), displayed in blue, and LUC from yield change (corrected from production change), displayed in red. Vertical bars on the righthand side represent range of the sensitivity tests for each specific effect.

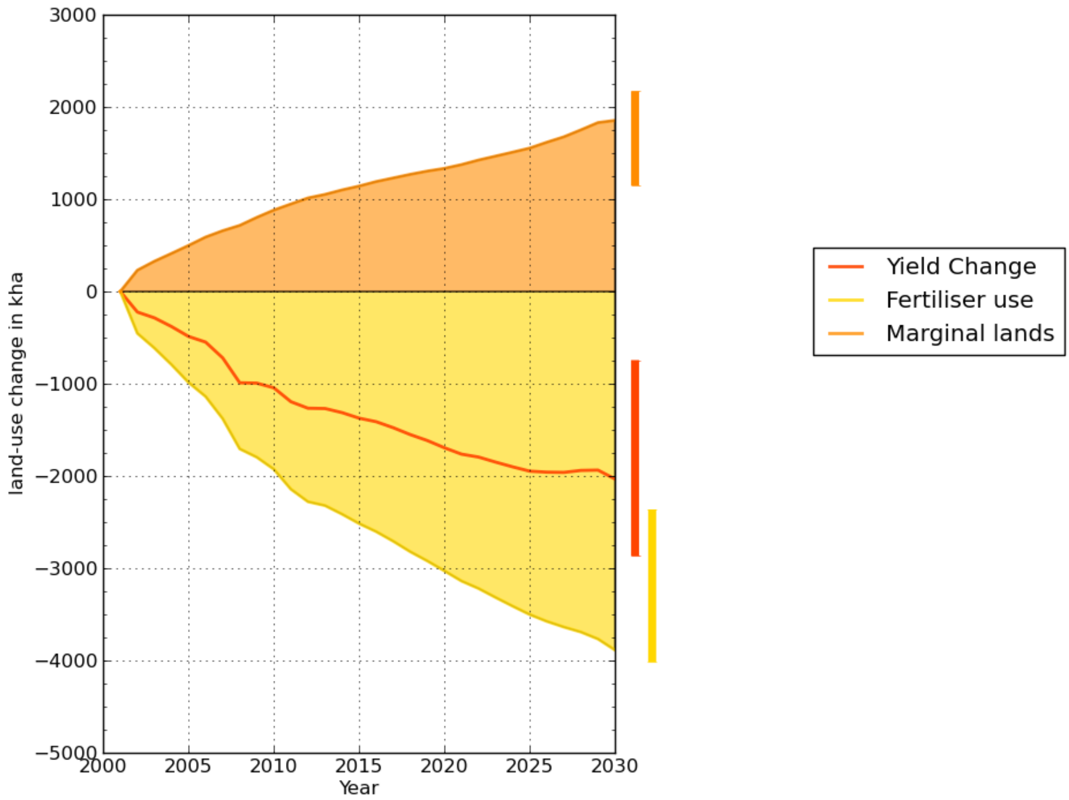

Figure 4: Decomposition of LUC resulting from yield change (red line) distinguishing the yield gain from the increased inputs use (yellow - negative LUC) and the yield loss from the expansion on marginal lands (orange - positive LUC). LUC from yield change is the sum of the yield gain from the increased inputs use and of the yield loss from the expansion on marginal lands. Vertical bars on the righthand side represent range of the sensitivity tests for each specific effect.

ing the production among regions makes it possible to benefit from unused productivity gain potential and to achieve larger yield increases. Finally, the increased pressure on land resulting from a shock in biofuel production triggers a higher intensification of livestock production, in addition to that of crop production. As a result, grass is substituted by crops in the animal feed ration. Intensifying the livestock production makes it possible to spare pasture lands to some extent, but generates an additional demand for cropland. We estimate this additional demand as about 200 kha.

By bringing together Fig. 4 and Fig. 5, we get the overall decomposition of land-use changes relative to the reference (see Fig. 6). This graph corresponds to the numerical evaluation of Eq. 7.

3.2.2 Regional scale

Results at the regional scale are shown in Fig. 7. As expected, the largest LUC, as well as the largest price increase, occur in Europe. Rest of Latin America (South and Central America without Brazil), OECD Pacific (Japan, Australia and New-Zealand) and the Former Soviet Union are the three non-European regions estimated to experience the largest LUC. LUCs are almost equally shared between Europe and the Rest of the World, with the former accounting for ~51% of total LUC and the latter for ~49%. Such a distribution between domestic LUC and LUC abroad has been found in other studies, notably Hertel et al. (2010). The bars showing the sensitivity range indicate that negative or almost zero LUC are possible in all regions except Europe.

LUC decomposition in the 12 regions used by the model is displayed in Fig. 8. LUC due to the biofuel production occurs only in Europe because of our assumption that the shock in production takes place entirely in Europe. Europe's balance of trade with respect to the rest of the world decreases by ~2 Mtoe (~80 PetaJoules), mostly in the direction towards the Rest of Latin America (21%), Africa (16%) and Rest of Asia (14%). Expressed in terms of areas (i.e., quantities traded divided by regional yields), Europe's balance of trade deteriorates by ~1100 kha relative to the reference scenario, while that of the rest of the world improves by 1800 kha; the gap between the two figures being explained by yield disparities across regions. Africa, Rest of Latin America and the Former Soviet Union are the three regions to experience the largest LUC resulting from international trade. Larger yield losses due to cropland expansion on to marginal lands occur in Europe, OECD Pacific and Rest of Latin America, while lower yield losses occur in Canada, Brazil and India. OECD Pacific is the only region where yield loss from conversion of marginal land is larger than yield gain from increased fertiliser use. In other regions, the former effect amounts to a maximum of ~50% of the latter one (in Rest of Asia, Europe and Latin America) and to a minimum of 2%-5% in Canada and Brazil.

Looking at the LUC mechanism shown in Fig. 8 provides a more detailed picture of indirect effects from a biofuel shock. We see in particular how yield responses drive the size of LUC in each region: in some regions, changes in production are largely compensated by yield increases, thus limiting the size of LUC. This is especially the case for Africa, which experiences smaller LUC than OECD Pacific, FSU, and Rest of Asia in spite of a larger production change. Other regions are conversely characterised by low yield responses, leading to relatively large LUC. This is especially the case of OECD Pacific, where the additional production leads to a decrease in the mean yield, as yield losses due to the cultivation of

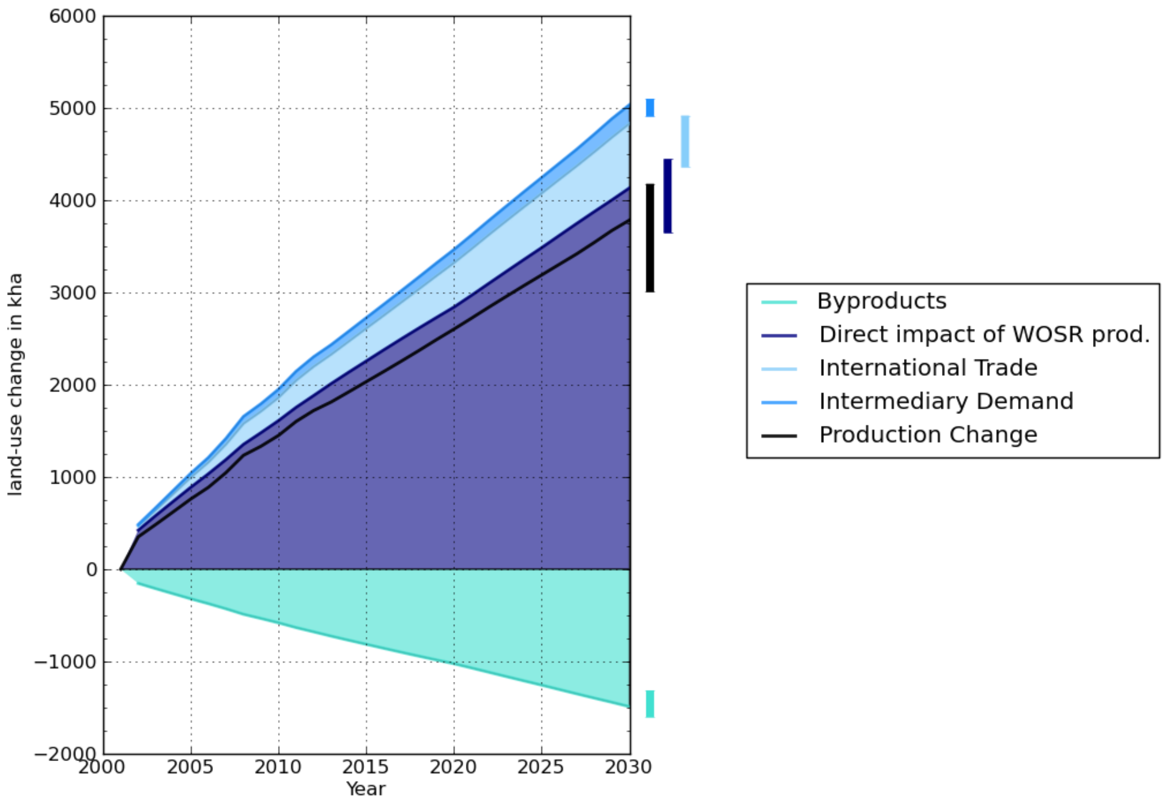

Figure 5: Decomposition of LUC resulting from production change (black line) distinguishing LUC resulting from the direct impact of the WOSR production (navy blue), the gain in LUC from by-products (turquoise), LUC from international trade (light sky blue), and LUC from change in intermediary demand (dodger blue). Vertical bars on the righthand side represent range of the sensitivity tests for each specific effect.

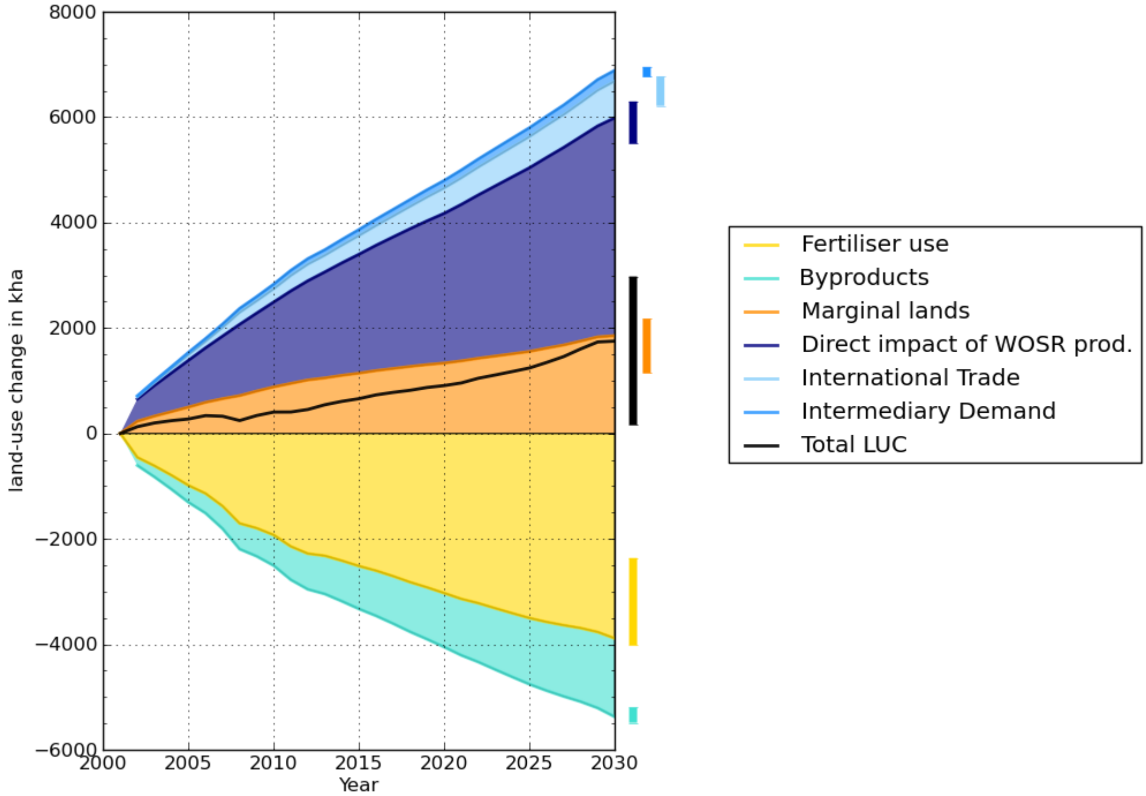

Figure 6: Decomposition of net global LUC combining the effects displayed on Fig. 4 and Fig. 5. Vertical bars on the righthand side represent range of the sensitivity tests for each specific effect.

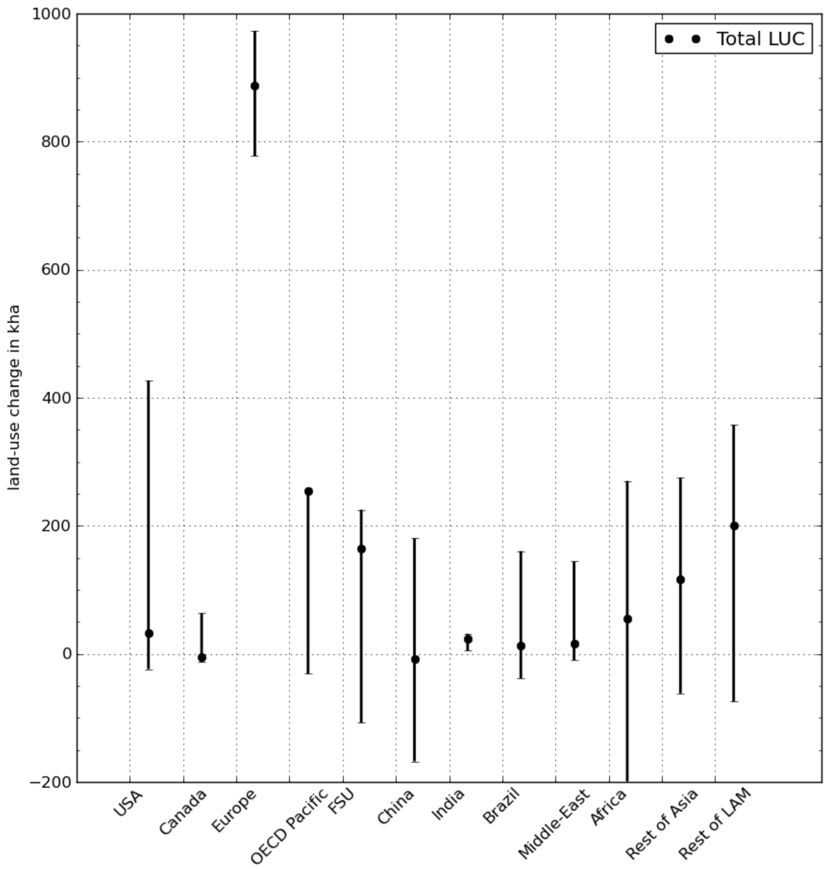

Figure 7: Modelled regional net land-use change due to the biofuel WOSR production shock. Bars represent range of the sensitivity tests.

marginal lands outweigh yield gains from the use fertiliser.

To pinpoint the different regional intensification/extensification patterns, yield- and area-price elasticities are calculated and normalized to sum to unity, as only relative values are meaningful (Nelson et al., 2014) (see Fig. 9). Results show that Canada, China, Brazil, Africa, India, USA and the Middle-East are characterised by the dominance of yield response (intensification), while OECD Pacific, Rest of LAM, Rest of Asia, FSU and Europe are characterized by the dominance of area response (cropland expansion). Patterns of yield/area responses for given land and fertiliser prices are governed by regional intensification and extensification potentials. In NLU, intensification potentials depend mainly on the regional yield gaps between actual and potential yield and the extensive margin[3], while extensification potential depends mainly on the amount of extensive pasture available for cropland expansion.

The values reported in Table 3 make it easier to understand why some regions are more or less yield-responsive than others and to elucidate some counter-intuitive results. We were, for instance, expecting a much larger area response for Canada, as this country has important reserves of unused lands. This land is, however, forested, while areas of extensive pastures, on which cropland area can actually expand in NLU, are small both in absolute and relative terms. Note that the deforestation scenario used in this study reproduces past trends, and therefore assumes a 0% deforestation rate for Canada. This explains why reserves of extensive pasture remain low in 2030. A larger deforestation rate up to 2030 would certainly significantly increase the Canadian area response.

Canadian land use has an other characteristic that is also found in Brazil: while the extensive margin of all regions of the world ranges between 0.16 (China) and 0.63 (Europe) in 2001 (model base year), it is almost equal to one in Canada and higher than 0.8 in Brazil (see the seventh column of Table 3). As a result, these two countries experience the lowest yield losses from conversion of marginal lands among the 12 regions studied. This explains why Brazil has a larger yield response than the Rest of Latin America, whereas these two regions have approximately the same gap between actual and potential yields and the same proportion of extensive pastures: ~50% of the yield gains from fertiliser use are compensated by yield losses from the conversion of marginal lands in the Rest of Latin America, against only ~5% in Brazil.

A final question is why Africa has such a larger yield response than the FSU, when these two regions have comparable yield gaps, proportion of extensive pasture and extensive margin. The answer here is to be found in the pathways of agricultural demand experienced by these two regions to 2030: propelled by a population increasing by ~84% between 2001 and 2030, African food demand increases by 95% for vegetal products and by ~130% for meat and milk-products. By contrast, food demand in FSU is projected to increase only by 1% for vegetal products and by 28% for animal products. Thus, Africa is on an intensive agricultural pathway, closing its yield gap by more than 20 percentage points up to 2030, whereas FSU is on an extensive pathway, closing its yield gap by only ~13%.

[3] as a reminder, the extensive margin is defined here as one minus the ratio between the mean potential yields on extensive pastures and on cropland

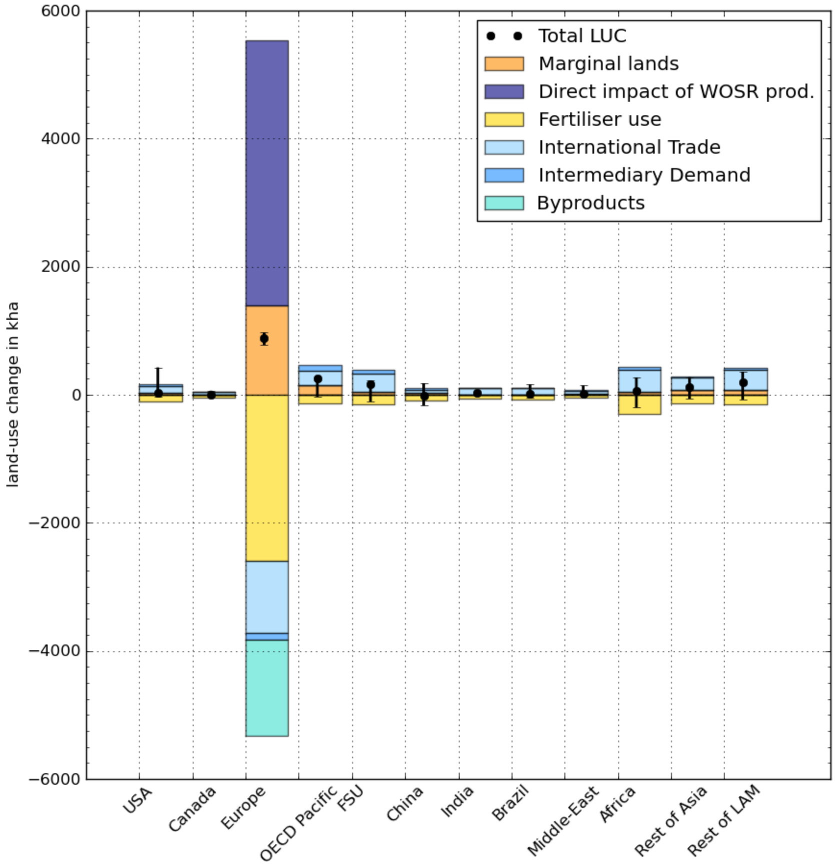

Figure 8: Decomposition of net regional land-use change for the 12 regions used by NLU.

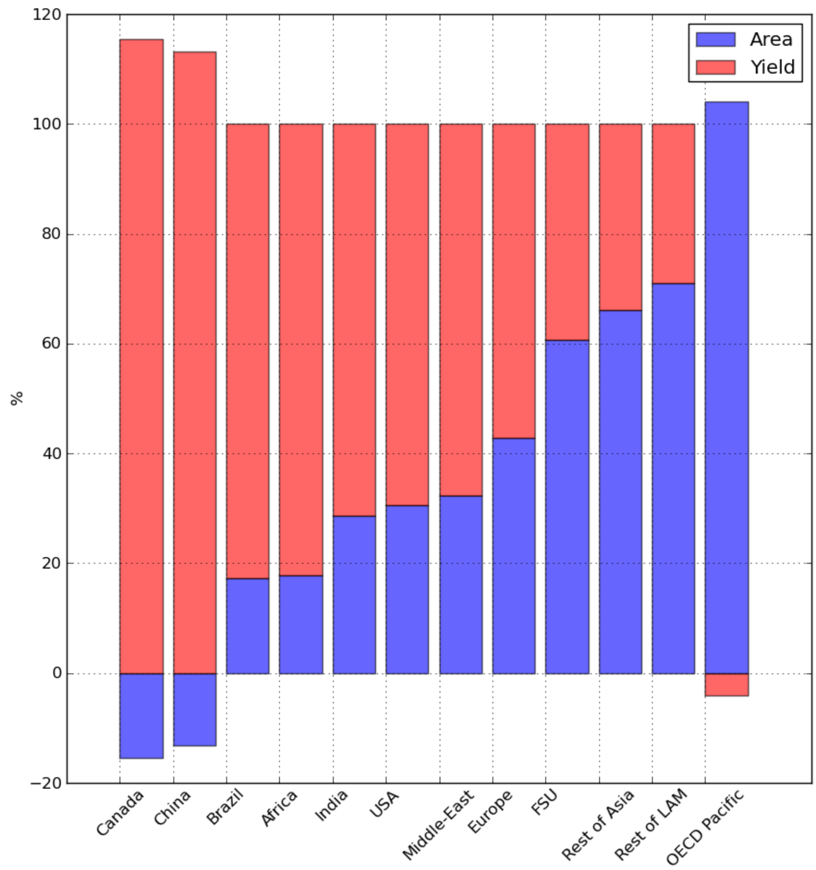

Figure 9: Regional relative yield / area response to the external WOSR shock in Europe. For example Rest of LAM (ninth bar from the left) meets its increase in production from the WOSR shock in Europe by ~30% from yield changes and by ~70% from area changes. Regions area ranked in order of increasing blue bar.

Table 3: Gap between actual and potential yield (yield gap), areas of extensive pastures, percentage of extensive pastures out of total agricultural area, mean potential yield on extensive pasture, gap between mean potential yield on extensive pasture and on cropland area (extensive margin). See region map in SI for definition of the regions.

Regions	Years	Yield Gap	Ext. past. area (Mha)	% of ext. past. on total agri. area	Extensive margin
USA	2001	39.4%	177	50.7%	0.32
	2030	20.8%	131	38.3%	0.37
Canada	2001	54.6%	13	23.9%	0.99
	2030	32.5%	10	19.5%	1.2
Europe	2001	46.5%	4	2.0%	0.63
	2030	27.9%	0	0.1%	0.04
OECD Pac.	2001	63.4%	255	84.3%	0.30
	2030	50.8%	244	74.9%	0.35
Former Soviet	2001	74.8%	324	68.7%	0.57
Union	2030	61.7%	304	64.6%	0.59
China	2001	37.3%	192	48.6%	0.16
	2030	21.6%	108	33.4%	0.16
India	2001	50.0%	6	4.0%	0.49
	2030	14.9%	1	0.9%	0.50
Brasil	2001	46.4%	97	44.4%	0.81
	2030	33.8%	106	36.8%	0.85
Middle-East	2001	62.3%	78	73.2%	0.36
	2030	39.1%	65	60.6%	0.38
Africa	2001	82.5%	700	77.0%	0.58
	2030	62.2%	685	67.5%	0.60
Rest Asia	2001	44.7%	119	51.5%	0.31
	2030	29.3%	108	39.0%	0.35
Rest Latin	2001	61.0%	287	72.7%	0.59
America	2030	46.8%	286	62.8%	0.42

4 Conclusion

In this paper, we have shown that LUC from an external shock to supply or demand can be arithmetically decomposed as the sum of LUC from production changes and LUC from yield changes. Both types of change can be further arithmetically decomposed. Each element of this LUC decomposition has been estimated using the NLU model in the case of supply shock of 4 Mtoe of winter oilseed rape. We estimated that the global land-use change from this supply shock amounts to 1730 kha, with an error ranging from 170 kha to 3000 kha.

These results are rather on the upper range of the estimates given by the literature. One explanation lies in our estimates of the extensive margin which are generally lower than those given in the existing literature (Hertel et al., 2010; Taheripour et al., 2012). This discrepancy results from the consideration of crop-livestock interactions and the asumption that intensive pasture, which produce grass in complement to food crop to feed animals, are not substitutable for cropland. As a consequence, this paper finds that nearly half of the yield gains from the increased use of fertiliser (in response to price) are compensated by yield losses originating from the conversion of marginal lands for crop production.

Our sensitivity analysis shows that most of the variance is explained by the sensitivity on the accessibility parameter. The consideration of land accessibility for estimating the extensive margin is a limitation which was flagged by Taheripour et al.. In this paper, we make a step forward by constraining the availability of extensive pasture for crop production. The constraint is progressively relaxed over the simulation in response to the growing pressure on land (approximated by the land rent), however this modelling is still coarse and associated with large uncertainties. In this regard, significant progress could be made by including land accessibility dataset in our modelling framework (e.g., from Verburg et al. (2011)).

Beyond numerical results, this paper also brings some insights that enable us to better understand the LUC mechanism linking production change and yield change, as well as the intensification/extensification patterns of the different world regions. This latter point is key to correctly predicting land-use change. It remains however controversial among the main global models of land-use as evidenced by the large discrepancies on the implicit aggregate model elasticities calculated by Nelson et al. (2014). The analytical framework proposed in this study proved useful to explain the regional intensification/extensification patterns and could be used as a diagnosis procedure to make the different processes modelled in numerical experiments more explicit.

We have applied our methodology to first generation biofuel which is still the critical method of producing biodiesel fuel even though the recently revised European directive on renewable energy has set a 7% cap on the amount of first generation biofuel that can be counted towards the 10% target for renewables in the transport sector. First generation biofuel is however only an example of application. It received our preference because of the wide availability of references to which to compare our results. The methodology developed in this paper could be used for other types of change affecting the agricultural system, in particular second generation biomass energy in which the plant cellulose is also used. Large-scale production of eucalyptus or miscanthus is indeed a strong option for producing the negative greenhouse gases emissions which are key to reaching the lowest pathways of global temperature change. Even if such bioenergy crops are deemed as not generating ILUC, their land-use impacts are however still unclear.

Significant limitations to this work should be mentioned. First, we do not take into account possible change in final demand in response to price change whereas this effect accounts for around 20% of the market-mediated effects estimated by Hertel et al.. Also, composition effects resulting from substitution among crops are not correctly taken into account as we consider a unique representative crop. Our results on global land-use change could be overestimated because of these two limitations.

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