Unravelling land-use change mechanisms at global and regional scales
Supplementary Information

June 13, 2018

1 Description of the modelling system and NLU regions

- **Economic dynamics**
  - Cost minimisation under supply/demand equilibrium on food and bioenergy markets
  - Ricardian principles accounting for accessibility constraints

- **Inputs**
  - Population
  - Food per cap
  - Bioenergy
  - Forest area
  - Energy prices

- **Nexus Land Use (NLU)**
  - Global scale model of agricultural intensification

- **Outputs**
  - Cropland area
  - Pasture area
  - Crop yield
  - Fertiliser cons.
  - Trade
  - Calorie / land prices

- **Biophysical parameters**
  - Feed ratio and composition (Bouwman et al., 2005)
  - Potential crop yield for 11 CFT (ULiM)
  - Global land cover at 0.5°x0.5° (Ramankutty, 2008)
2 Data

Data are available on the following webpage: https://poseidon.centre-cired.fr/data_process-based-decomposition-paper/. There is one directory per run. Outputs can be found in the sub-directory whose name is given by date-hour. Global results are in the file simulation_global_results.csv; regional results are in simulation_result_ny30.csv.

3 Slopes at the origin of the yield-fertiliser function

4 Model equations

The NLU model simulates changes in the agricultural sector at the global scale (food price, land rent, profit, crop yield and the share of cropland areas in total agricultural lands) with a non-linear response of yield to fertilizer prices, as well as an explicit representation of livestock systems and international trade.

At the base year, a representative potential yield is computed on a 0.5° × 0.5° grid from the potential yields given by the vegetation model LPJmL for 11 crop functional types (CFT). Land classes grouping together grid points with the same potential yield are set up. Yield in each land class is determined by a function of fertilizers. This function asymptotes toward the potential yield and is characterised by decreasing returns. In each land class, consumption of chemical inputs and associated yield are determined by cost minimization under the constraint a global supply demand balance of plant food (Eq. 3) and ruminant calories (Eqs. 4–7) and a land constraint (Eq. 9).
Indices

\( j \)  
Land class number.

\( j_{\text{limit}} \)  
Limit land class between the intensive and the extensive production systems.

\( j_{\text{max}} \)  
Index of the highest land class.

Parameters in each region

\( \omega_{\text{swo}}^{\text{fc}}, \omega_{\text{swo}}^{\text{m}}, \omega_{\text{swo}}^{r} \)  
Share of Seed, Waste at the farm level, Other uses of food crops excluding agrofuel production and Feed (only for monogastrics and ruminants) in total production of Food Crop, Monogastric and Ruminant products.

\( Q_{\text{other crop}}^{\text{fc}} \)  
Other production of food crops which is not dynamically modelled (i.e. difference between the total production from Agribiom and LPJmL production in 2001).

\( \alpha_{\text{IC}} \)  
Initial slope of the intermediate consumption function in \( \$ \text{ kcal}^{-1} \).

\( \text{FC}_{\text{tot}} \)  
Fixed cost per hectare in \( \$ \text{ ha}^{-1} \text{ yr}^{-1} \) corresponding to capital, labour, business services, pesticides and energy consumption for vehicles, buildings (heating, etc.) and other on-farm operations (drying of crops, etc.). Recalibrated to account for the costs of the intensive and the extensive systems.

\( \rho_{\text{grass}}^{\text{past}, \text{int}}, \rho_{\text{grass}}^{\text{past}, \text{ext}} \)  
Grazed grass per hectare of intensive and extensive pastures in \( \text{kcal ha}^{-1} \text{ yr}^{-1} \).

\( \rho_{\text{r}, \text{int}}^{\text{past}}, \rho_{\text{r}, \text{ext}}^{\text{past}} \)  
Production of ruminant product per hectare of intensive and extensive pastures in \( \text{kcal ha}^{-1} \text{ yr}^{-1} \) (\( \rho_{\text{past}}^{\text{r}, \text{int/ ext}} = \frac{\rho_{\text{past}}^{\text{r}, \text{int/ ext}}}{\rho_{\text{past}}^{\text{r}, \text{int/ ext}}} \)).

\( \text{Imp}^{\text{m}}, \text{Exp}^{\text{m}} \)  
2001 imports and exports of monogastric products in \( \text{kcal yr}^{-1} \). Potential yield and minimum (no inputs) yield in \( \text{kcal ha}^{-1} \text{ yr}^{-1} \).

\( \beta_{\text{m}}, \beta_{\text{r}, \text{int}}, \beta_{\text{r}, \text{ext}} \)  
Feed conversion factor for monogastrics, intensive and extensive ruminants in kcal of feed/kcal of animal product.

\( \phi_{\text{fc}}, \phi_{\text{m}}, \phi_{\text{fodder}}, \phi_{\text{r}, \text{int}}, \phi_{\text{r}, \text{ext}}^{\text{fc}}, \phi_{\text{r}, \text{int}}, \phi_{\text{r}, \text{ext}}^{\text{grass}}, \phi_{\text{r}, \text{int}}^{\text{grass}}, \phi_{\text{r}, \text{ext}}^{\text{grass}} \)  
Share of feed categories in animal rations (fc: food crops, fodder: residues and fodder, grass: pasture grass, monogastrics, r,int: intensive ruminants, r,ext: extensive ruminants).
World level variables

\( p_w^{cal} \) World calorie price in $ kcal\(^{-1}\) (endogenous).

\( p_x \) Index of fertilizer and pesticide price (exogenous).

Exogenous regional variables

\( D_{fc}^{h}, D_{m}^{h}, D_{r}^{h} \) Demand of food crops (fc), monogastrics (m) and ruminants (r) products for humans (h) in kcal yr\(^{-1}\).

\( D_{agrofuel}^{fc} \) Demand of food crops for agrofuel production in kcal yr\(^{-1}\).

\( S_{surf} \) Supply of agricultural area excluding other croplands, including dynamic croplands, extensive, intensive and residual pastures in ha.

Endogenous regional variables in each land class

\( \rho_j \) Yield of the land class \( j \) minimizing farmer’s production cost in kcal ha\(^{-1}\) yr\(^{-1}\).

\( IC_j \) Intermediate consumption of chemical and mineral inputs of the land class \( j \) in $ ha\(^{-1}\) yr\(^{-1}\).

\( f_j^{crop}, f_j^{int}, f_j^{pres}, f_j^{pext} \) Area of dynamic cropland (i.e. where crops modelled in the LPJmL model are grown), intensive pastures, residual pastures, extensive pastures of the land class \( j \) expressed as a fraction of \( D_{surf} \).

Endogenous regional variables

\( p_{cal} \) Food crop calorie price in $ kcal\(^{-1}\).

\( \lambda \) Land rent in $ ha\(^{-1}\) yr\(^{-1}\).

\( p_r \) Price of ruminant calories in $ kcal\(^{-1}\).

\( D_{surf} \) Demand of agricultural area excluding other croplands, including dynamic croplands, extensive, intensive and residual pastures in ha.

\( Q_{r,int}, Q_{r,ext} \) Intensive, extensive ruminant production in kcal yr\(^{-1}\).

\( D_{m}^{fc}, D_{r,int}^{fc} \) Demand of food crops for monogastrics and intensive ruminant production in kcal yr\(^{-1}\).

\( D^{fc} \) Total demand of food crops in kcal yr\(^{-1}\).

\( Imp^{fc}, Exp^{fc} \) Imports and exports of food crops in kcal yr\(^{-1}\).

\( Imp^{r}, Exp^{r} \) Imports and exports of ruminant products in kcal yr\(^{-1}\).
Yield-fertilizer function:

\[ IC_j(\rho_j) = \alpha IC(\rho_j^{\text{max}} - \rho_j^{\text{min}}) \left( \frac{\rho_j^{\text{max}} - \rho_j^{\text{min}}}{\rho_j^{\text{max}} - \rho_j} - 1 \right) \]  

(1)

Objective function: Cost minimization of total production costs in each region:

\[ \text{Min}_{\rho_j, j, j^{\text{limit}}, D_{\text{fc}} r, \text{int}, Q r, \text{int}, Q r, \text{ext}, D_{\text{surf}}} \left( \int_{j^{\text{limit}}}^{\text{max}} (p_j IC_j(\rho_j) + FC_{\text{tot}}) f_j^{\text{crop}} d_j \right) D_{\text{surf}} \]  

(2)

Regional constraints:

\[ Q_{\text{fc}}^{\text{other}} + \int_{j^{\text{limit}}}^{\text{max}} f_j^{\text{crop}} \rho_j d_j D_{\text{surf}} = (D_{r, \text{int}}^{\text{fc}} + D_{h}^{\text{fc}} + D_{m}^{\text{fc}} + D_{\text{agro}}^{\text{fc}} + Exp^{\text{fc}} - Imp^{\text{fc}})(1 + \omega_{\text{swc}}) \]  

(3)

\[ D_{h}^{\text{fc}} + \text{Exp}^{r} - \text{Imp}^{r} = Q_{r, \text{int}} + Q_{r, \text{ext}} \]  

(4)

\[ D_{m}^{\text{fc}} + \text{Exp}^{m} - \text{Imp}^{m} = Q_{m} \]  

(5)

\[ Q_{r, \text{ext}} = \left( \int_{0}^{\text{limit}} f_j^{\text{ext}} d_j + \int_{\text{limit}}^{\text{max}} f_j^{\text{pres}} d_j \right) \rho_j^{\text{ext}} D_{\text{surf}} \]  

(6)

\[ Q_{r, \text{int}} = D_{r, \text{int}}^{\text{fc}} \]  

(7)

\[ Q_{m} = D_{m}^{\text{fc}} \]  

(8)

\[ S_{\text{surf}} = D_{\text{surf}} \]  

(9)

The constraint on food crop production (Eq. 3) is associated to the lagrangian multiplier interpreted as the calorie price \( p_{\text{cal}} \). The constraints on total ruminant production (Eq. 4), extensive (Eq. 6) and intensive (Eq. 7) ruminant production are associated to lagrangian multipliers that are all equal and can be interpreted as the ruminant price \( p_{r} \). The constraints on monogastric production (Eq. 5 and 8) are associated to lagrangian multipliers that are all equal and can be interpreted as the ruminant price \( p_{m} \). Finally, the land constraint (Eq. 9) is associated to the lagrangian multiplier interpreted as the land rent \( \lambda \).
First order conditions yields:

\[ p_{cal} = p_f(\chi_j(\rho_j) + \omega_{swd}) \]  
\[ p_r = p_{cal}(1 + \omega_{swo}) + \beta_{r,int}\phi_{r_int} \]  
\[ p_m = p_{cal}(1 + \omega_{swd}) + \beta_m\phi_{m_c} \]  
\[ p_{r,ext} = (p_{cal}\rho_{j,limit} - p_f(\chi_j(\rho_j) + FC_{tot})f_{j,limit}^{\text{crop}} + p_r f_{j,limit}^{\text{Pres}}) \]  
\[ \lambda = p_{cal}\int_{j,\text{limit}}^{j,\text{max}} f_{j,\text{crop}}\rho_{j,\text{limit}} d_j - \int_{j,\text{limit}}^{j,\text{max}} (p_f(\chi_j(\rho_j) + FC_{tot})f_{j,\text{crop}} d_j \ldots \]  
\[ \delta = \lambda - \mu \]

The land rent \( \lambda \) is the sum of the scarcity rent, denoted \( \mu \), and the differential rent, denoted \( \delta \), defined as following:

\[ \mu = p_{cal}f_{j,\text{limit}}^{\text{crop}}\rho_{j,\text{limit}} - (p_f(\chi_j(\rho_j) + FC_{tot})f_{j,\text{limit}}^{\text{crop}} + p_r f_{j,\text{limit}}^{\text{Pres}}) \]  
\[ \delta = \lambda - \mu \]

References

Table 1: Slopes at the origin of the yield-fertiliser function in 2050 for the regions used in the NLU (see regions map in SI). Values of the slopes are given for NLU default case and for the FAO projections of Alexandratos and Bruinsma (2012). In $/Mkcal ($ of fertilizer used to generate a MKcal of crop).

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<tr>
<th>Region</th>
<th>NLU - default</th>
<th>NLU - FAO</th>
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