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Motivations for developing downscaling of land use and land-cover changes

Global models (multiregional) cannot produce results at fine resolutions

Local models oversee global drivers and tendencies. Conversely, aggregate global models miss local implications, drivers, processes, uncertainties

New estimation problem; fine resolution information/data recovery from aggregate scales using all available information

Although GIS provides detailed geographical information, the social, economic, environmental data and drivers usually exist on aggregate level, e.g., national, regional

Local – global interdependencies

Approach: fussion (integration) of Global Biosphere Management (GLOBIOM) partial equilibrium land use planning model and probabilistic (in general, non-Bayesian) downscaling to “project” GLOBIOM results to finer resolutions

At IIASA – assessment and downscaling of GLOBIOM SSP (Shared Socio-economic Pathways) scenarios for IPCC AR-5 report
GLOBIOM is a land use planning model producing projections of land use and l.c. changes:

Recursive dynamics: land use change transmitted from one period to another

⇒ Limited land availability!
GLOBIOM is a multi-sectoral model

**LAND USE**
- Wood
- Sugarcane
- Corn
- Cassava
- Soybeans
- Wheat
- etc...

**PRIMARY PRODUCTS**
- Cattle
- Sheep and Goats
- Pigs
- Poultry

**PROCESS**
- Saw and Pulp mills
- Refineries
- Slaughterhouse

**FINAL PRODUCTS**
- Sawn wood
- Pulp
- Biofuel
- Biogas
- Fuel wood
- Heat
- Crops for Food
- Lamb
- Beef
- Pork
- Chicken
- Eggs
Combination of biophysical and economic models

Land productivity depends on geography (climate, soil, altitude, slope, etc.)

Deterministic optimization problem: to achieve the highest consumption level at the lowest cost under constraints on land availability, environmental pollution, etc.

Stochastic optimization problem - yields/weather, supply, prod. costs, demand elasticities are in general stochastic; to achieve highest consumption at lowest cost under food security constraints (represented by means of VaR or CVaR type constraint)
The economic model:

- **Recursive dynamic**: solution computed every 10-year period and transmitted to the next period

<table>
<thead>
<tr>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>...</th>
</tr>
</thead>
</table>

**Main exogenous drivers**
- Population growth
- GDP growth
- Technological change
- Bio-energy demand (POLES team)
- Diet patterns (FAO, 2006)

**Main model outputs**
- Land use change
- Production
- Consumption
- Prices
- Trade flows
- Water use
- GHG emissions
A global model with the possibility to zoom into one region and …

30 Regions are interconnected through international trade
... downscale into grid cells

2010
(CrpLnd)
Land uses and land use changes allowed in GLOBIOM

**Land uses**
- Crop land          Natural forest
- Grass land         Planted forest
- Natural land

**Land use transformations**
- Crop land to Planted forest
- Natural forest to Grass land
- Grass land to Planted forest
- Natural land to Planted forest
- Crop land to Natural land
- Grass land to Natural land
- Natural forest to Crop land
- Grass land to Crop land
- Natural land to Crop land
- Natural land to Grass land
- Planted forest to Natural land
Land use change

downscaling:
GLOBIOM model

Land use type
Region
Time
Land in land use
Land converted from $i$ to $j$ in region $r$ and time $t$

Finer resolution – simulation units (SimUs)

At regional level

$$A_{ir}^{t} = A_{ir}^{t-1} + \sum_{j} \Delta A_{ijr}^{t} - \sum_{j} \Delta A_{jir}^{t}$$

At SimU (grids) level $l$

$$A_{ilr}^{t-1} + \sum_{l} z_{ijlr}^{t} \Delta A_{ijr}^{t} - \sum_{l} z_{jilr}^{t} \Delta A_{jir}^{t} = A_{ilr}^{t}$$
Downscaling problem

Find shares \( z_{ijlr}^t \) of aggregate area change transformed from \( i \) to \( j \) in \( l \) that

\[
\sum_j z_{ijlr}^t \Delta A_{ijr}^t = \Delta A_{ijr}^t \quad \text{i.e.} \quad \sum_l z_{ijlr}^t = 1
\]

\[
A_{ilr}^{t-1} + \sum_l z_{ijlr}^t \Delta A_{ijr}^t - \sum_l z_{jilr}^t \Delta A_{jir}^t = A_{ilr}^t
\]

\[
\sum_{i=1}^m A_{ilr}^t = L_r^t
\]

Cross-entropy: Maximize Kulback-Leibler information distance

\[
\sum_{j=1}^n \sum_{i=1}^m \sum_{l=1}^m \left( z_{ijlr}^t \ln(z_{ijlr}^t / q_{ijlr}^t) \right) \quad \sum_l q_{ijlr}^t = 1 \quad \text{- prior probability}
\]
Maximum Entropy and Minimax Likelihood

Maximal Likelihood: let random value \( \xi \) has \( N \) independent observations:

\[ \xi(1), \ldots, \xi(N) \quad \text{The problem is to estimate the true probability distribution:} \]

\[ \text{Pr}[\xi = \xi_j] = p_j \quad \text{by maximizing the probability of observing the sample:} \]

\[ \prod_{k=1}^{N} \text{Pr}[\xi = \xi(k)] = \prod_{j=1}^{r} p_j^{v_j} \quad \text{subject to} \quad \sum_{j=1}^{r} p_j = 1, \quad p_j > 0, \quad \sum_{j=1}^{r} v_j = N \]

or maximizing

\[ \ln \prod_{j=1}^{r} p_j^{v_j} = \sum_{j=1}^{r} v_j \ln p_j \quad \text{solution is} \quad p_j^N = v_j / N \]

The log-likelihood function is the sample mean approximation of the

\[ E p_\xi = \sum_{j=1}^{r} p_j^* \ln p_j \]

In downscaling, information is given not by observations but by various constraints connecting the distribution with characteristics of observ. variables

Let \( P \) be a set of all possible distributions satisfying constraints:

\[ x = (x_1, \ldots, x_r) \in P \]

**Proposition:** If \( x = (x_1, \ldots, x_r) \in P \), then

\[ \max_{p \in P} \sum_{j=1}^{r} x_j \ln p_j = \sum_{j=1}^{r} x_j \ln x_j \]

And, the “worst case” principle leads to the

\[ \min_{p \in P} \max_{x \in \mathbb{P}} \sum_{j=1}^{r} x_j \ln p_j = \min_{p \in P} \sum_{j=1}^{r} x_j \ln x_j \]
Examples of priors

Priors for downscaling aggregate land use changes are estimated based on comparative profitability of land use activities.

**Crop land to Planted forest**

\[
q_{l,r,CropL_{-}Plt}^t = \frac{(\phi_{lr}^t)^{-1} y_{Plt,l,r}^t A_{Plt,l,r}^{t-1} (\Pi_{lr}^t)^{-1}}{\sum_l ((\phi_{lr}^t)^{-1} y_{Plt,l,r}^t A_{Plt,l,r}^{t-1} (\Pi_{lr}^t))^{-1}}
\]

- Yield of planted forest
- Crop land production value
- Normalized transportation time
- Average time to closest market
Grass land to Planted forest

\[ q_{l,r,\text{Grass}_L,\text{Plt}}^t = \frac{(\varphi_{lr}^t)^{-1} y_{\text{Pltlr}}^t A_{\text{Pltlr}}^{t-1} (y_{\text{Grass},l,r}^t A_{\text{Grass},l,r}^{t-1})^{-1}}{\sum_l ((\varphi_{lr}^t)^{-1} y_{\text{Pltlr}}^t A_{\text{Pltlr}}^{t-1} (y_{\text{Grass},l,r}^t A_{\text{Grass},l,r}^{t-1})^{-1})} \]

Yield of planted forest

Crop land production value

Normalized transportation time

Average time to closest market

Yield of planted forest

Grass land yield
Forest land to Crop land

\[ q_{l,r,ForestL,CropL}^t = \frac{\left( y_{l,r,Forest}^t A_{l,r,Forest}^{t-1} P_{l,r,Forest}^t \right)^{-1} \Pi_{l,r}^t}{\sum_l \left( \left( y_{l,r,Forest}^t A_{l,r,Forest}^{t-1} P_{l,r,Forest}^t \right)^{-1} \Pi_{l,r}^t \right)} \]

Crop land production value

\[ \Pi_{l,r}^t = \sum_s P_{jr}^t y_{slr}^t A_{slr}^{t-1} \]

Forest yield

\[ y_{l,r,Forest}^t A_{l,r,Forest}^{t-1} \]

Timber price

\[ P_{l,r,Forest}^t \]
Dynamics of forest and planted forest land, 2010 – 2100, in 1000 ha
Optimal land use transition shares: “Crop to grass” and “crop to other natural land”, 2010–2100
Robust downscaling

A set of priors \( Q = \{ q^s, s = 1 : S \} \) defines alternative feasible distributions

The goal is to minimize the information distance with respect to the set \( Q \)

\[
F(z) = \max_s \sum_{i,j} z_{ij} \ln(z_{ij} / q^s_{ij}) = \sum z_{ij} \ln(z_{ij} / q^s_{ij}(z))
\]

\[
F(z) = \max_{\gamma} \sum_s \gamma_s \sum_{i,j} z_{ij} \ln(z_{ij} / q^s_{ij})
\]

\[
\sum_{s=1}^{S} \gamma_s = 1 \quad \gamma \in H
\]

e.g. \( \gamma_s \geq \gamma_t \), \( \gamma_s + \gamma_t \geq 1/2 \) for some \( s \) and \( t \)
Minimize $F(z)$ with respect to $z$. $F(z)$ is non-convex in $(z, \gamma)$:

$$F(z) = \max_{\gamma \in H} \sum_{s=1}^{S} \gamma_s \sum_{i,j} z_{ij} \ln(z_{ij} / q_{ij}^s) = \sum_{i,j} z_{ij} \ln z_{ij} + \min_{\gamma \in H} \sum_{s=1}^{S} \gamma_s \left( \sum_{i,j} z_{ij} \ln q_{ij}^s \right)$$

$$\min_{\gamma \in H} \sum_{s=1}^{S} \gamma_s \left( \sum_{i,j} z_{ij} \ln q_{ij}^s \right) \quad \sum_{s=1}^{S} \beta_{ks} \gamma_s \geq \delta_k \quad \beta_{ks} \quad \delta_k \quad k = 1, K$$

Denote $c_s := \sum_{i,j} z_{ij} \ln q_{ij}^s$

$$\min_{\gamma \in H} \sum_{s=1}^{S} \gamma_s c_s \quad \sum_{s=1}^{S} \beta_{ks} \gamma_s \geq \delta_k$$

**Dual problem**

$$\max_u \sum_{k=1}^{K} \delta_k u_k \quad \sum_{k=1}^{K} \beta_{ks} u_k \leq c_s \quad u = (u_1, \ldots, u_k)$$
Minimization of $F(z)$ w.r.t. $(z, \gamma)$

$$F(z) = \max_{\gamma \in H} \sum_{s=1}^{S} \gamma_s \sum_{i,j} z_{ij} \ln(z_{ij}/q_{ij}^s) = \sum_{i,j} z_{ij} \ln z_{ij} + \min_{\gamma \in H} \sum_{s=1}^{S} \gamma_s \left( \sum_{i,j} z_{ij} \ln q_{ij}^s \right)$$

is equivalent to minimization w.r.t. $(z,u)$ of

$$\sum_{i,j} z_{ij} \ln z_{ij} - \sum_k \delta_k u_k$$

s.t.

$$\sum_k \beta_{ks} u_k \leq \sum_{i,j} z_{ij} \ln q_{ij}^s \quad s = 1 : S \quad z \in Z$$

Comparison of results with a “Value of Stochastic Model” or “Value of Stochastic Solution”
Robust

2010 (CrpLnd)

Alternativ

2010 (CrpLnd)
Robust

2030 (CrpLnd)

Alternative

2030 (CrpLnd)
Robust

2010
(CrpLnd)

> 0.000  0.094  0.308  0.655  1.214  2.134  3.787  6.775  14.994  < 303.400
Robust
Robust
Robust