International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria

Email: joseph@iiasa.ac.at

Methodology

Optimization model for profit maximization in agricultural production

Modelling sustainable intensification of rice production in East Africa

Sustainable intensification of production is a viable option to meet increasing food demand, including rice demand, for a growing population in the East African Lake Victoria basin. We describe here how this can be modelled using biophysical and economic approaches.

Profit maximization

The model is built around the economic optimization of the sum of farmers' profits Π given by the main objective function:

$$\max \sum_{i,w,b} \Pi_{i,w,b} = \sum_{i \in \{conventional, mixed\}} \sum_{w \in \{rr,ii,ri,r0,i0\}} \sum_{b=1}^{61} \Pi_{i,w,b}$$

$$= \sum_{i \in \{conventional, mixed\}} \sum_{w \in \{rr,ii,ri,r0,i0\}} \sum_{b=1}^{61} \left[y_{i,w,b} * a_{i,w,b} * P_{i,b} - C_{i,w} * a_{i,w,b} - \rho * M_{i,w} - \tau * E \right]$$

The subscripts i, w, b denote production options and spatial entities. $i = \{low\_input,\ int\_mix\_input,\ int\_conv\_input\}$ is for inputs, where production options are agriculture with low levels of inputs, mixed intermediate levels of inputs or conventional inputs. See the data section for a detailed description of the underlying data. w stands for water, meaning irrigation options *rainfed* or *irrigated.* The 61 subbasins of the Lake Victoria Basin are denoted by the subscript b.

Profits are the sum of revenues which we calculate as production quantities given by the total area for rice production (a) multiplied by the attainable yield (y) and the price (P). From this, we subtract production costs (C) for growing rice in the respective area (a). Further, in some scenarios, emission costs given by emission price (ρ) per unit of greenhouse gas (CH_4 and N_2O) emission and transport costs given by export quantities (E) times unit transport costs (τ) reduce profits.

We calculate yields $y_{i,w,b}$ as attainable yields determined by biophysical factors ($\bar{y}_{i,w,b}$), including soil conditions and climate in GAEZ. We adjust these attainable yields by multiplying them with discount factors for agroecological practices (α_i), milling (β), cultivation conditions ($\gamma_{i,w,b}$), multicropping (δ_w) and changes in future weather (θ).

$$y_{i,w,b} = \alpha_i \beta \gamma_{i,w,b} \delta_w \theta \bar{y}_{i,w,b}$$

Constraints

The maximization problem above is constrained by land and water availability. The underlying data comes from modelling efforts using agricultural production and water supply models, respectively.

Land availability

Three separate constraints are imposed for land for rice production. First, in each production option in each sub-basin, the upper bound for the area for rice production is given by the very suitable and suitable physical area for rice production determined using the Global Agroecological Zones (GAEZ) methodology. We denote this area as $\bar{a}_{i,w,b}$. "Very suitable" and "suitable" are pre-defined suitability classes in GAEZ, determined mainly by the yields attainable in the area. Second, the combined rainfed and irrigated land under all input intensities allocated to rice cannot be larger in a sub-basin than the physical land available. Third, summing over rainfed and irrigated land, the land for each level of inputs in each sub-basin must be less or equal to the land available in a multi-cropping class. Multi-cropping classes are defined to reflect the agro-climatic multi-cropping potential of an area. The classes include:

Agro-climatic multi-cropping potential classes:

1 double rice cropping, both under rain-fed and irrigated conditions
2 single rice rain-fed, double rice irrigated
3 single rice cropping, both under rain-fed and irrigated conditions
4 No rice cropping rain-fed, double rice when irrigated
5 No rice cropping rain-fed, single rice when irrigated
6 Nor rice cropping, both rain-fed and irrigated (i.e., too cold)

An additional constraint on land is introduced in a model variant with agroecological inputs. Here, we assume that the sum of the area used for agroecological and conventional production of rice must be no more than the suitable area for production with conventional inputs.

Water availability

Water use is constrained by water availability Ω_b in the basin:

$$\sum_{i,w} [\omega_{i,w,b} * a_{i,w,b}] \leq \Omega_b$$

Where $\omega_{i,w,b}$ is the water requirement per hectare of land $a_{i,w,b}$.
We also compute the water requirements for each combination of irrigation and input intensities using the crop model in GAEZ.

Data

A substantial share of the data inputs for the optimization model are derived from the GAEZ and Community Water (CWatM) Model. GAEZ uses as inputs crop requirements and local biophysical conditions determining crop production such as land cover, soil characteristics and climate. The maximum area for rice production $\bar{a}_{i,w,b}$ in a subbasin is obtained by summing over all gridcells in the subbasin since this version of GAEZ computes all variables in a raster. Attainable yields before adjusting with discount factors ($\bar{y}_{i,w,b}$) is also derived from the gridded GAEZ outputs. The discount factors are assumed fixed and derived from literature. The discount factor for agroecological practices $\alpha_i < 1$ and the multicropping (δ_w) penalties are part of a scenario analysis and thus not set fixed. The paddy to milled rice conversion factor $\beta = 0.7$ was derived from expert elicitation with the International Rice Research Institute (IRRI). Cultivation factors $\gamma_{i,w,b}$ are outputs of GAEZ and changes in precipitation and temperature (θ) are employed by scaling the yields to resemble those of multiple percentiles realized in the past.

Scenarios

Scenarios are implemented to reflect yields in a reference case, the 5th, 10th, 15th, 20th, 25th and 30th percentile of the potential yield distributions in GAEZ and in addition from the same distribution the yields within one, two or three standard deviations from the mean as well as those for the outlier years 2010, 2009, 2005, 1993 and 1984. To explore the influences of conservation options, we further implement conservation options with high and low protection of land. High protection means rice is only grown on unprotected cropland but including wetlands. In addition, we model the sensitivity of the results to future climate scenarios using Representative Concentration Pathways (RCP) RCP2.6, RCP4.5, RCP6.0 and RCP8.5.