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A Market-Oriented Approach for Multiple Objective Optimization in Agro-Ecological Land Use Planning.

Per J. Agrell

A MARKET-ORIENTED APPROACH FOR MULTIPLE OBJECTIVE OPTIMIZATION IN AGRO-ECOLOGICAL LAND USE PLANNING

PER J. AGRELL

*Royal Veterinary and Agricultural University,
Department of Economics and Natural Resources
Rolighedsvej 23, DK-1958 Frederiksberg C, DENMARK*

ABSTRACT. The development of a third world country requires a conscious balance between different planning and policy issues, such as population growth rate, gross national income, self reliance and long-term sustainable ecological development. This paper reports on a cross-disciplinary project to design a decision support system (DSS) that aims to assist government policy makers in planning the regional agricultural development of the Bungoma region in Kenya. Contrary to previous research, which has taken the perspective of a central planner and a static market, this model extends the scope by introducing the market mechanisms and price subsidies. The model is based on the Agro-Ecological Zones (AEZ) model, a previously developed non-interactive optimization model that provides an agro-ecological and economic assessment of various types of land uses, including cash-crops, food production, grazing, forestation and farming. This paper maintains the decision analytic scope of the AEZ model to explicitly incorporate a multicriteria decomposition optimization formulation that facilitates a direct trade-off analysis between the various decision criteria within a user-interactive decision support modeling framework. The model uses in-depth information about the Bungoma region, extracted from a large scale FAO database on Kenya that includes information on various climatic and soil characteristics (*e.g.*, thermal and moisture regime, soil type, slope class) and socio-economic data (*e.g.*, projected growth rate and product demand patterns) for 90,000 agro-ecological cells. At each stage of the analysis, our system offers the decision maker several alternative planning strategies with different suggested land uses for over 100 different types of crops, fuelwood and livestock land utilization types for evaluation, allowing the decision maker to take into account trade-offs between a number of planning and policy criteria, including food output, net revenue, gross value of output, self sufficiency, production costs, arable land use and degree of erosion.

KEYWORDS: Decision Analysis, Multicriteria Decision Making, Integrated Land-Use Planning and Management, Decision Support Systems.

A MARKET-ORIENTED APPROACH FOR MULTIPLE OBJECTIVE OPTIMIZATION IN AGRO-ECOLOGICAL LAND USE PLANNING

INTRODUCTION

The long-term optimal usage of available land resources is a crucial challenge facing decision makers in many developing countries. Often heavily dependent on agricultural production for their immediate subsistence, export income and employment of the fast growing population, countries in middle Africa and south-east Asia are launching various judicial and educational programs to improve agricultural efficiency and reduce environmental degradation. A particular problem scenario arises when land degradation is caused by subsistence farming, as in Africa, rather than industrially induced deforestation, as in South-America and South-East Asia (FAO, 1995). In this case, lack of infrastructure and efficient local product markets necessitate local farmers to produce demanded goods irrespective of land yield potential and long-term side effects. The lower yields *per se* hamper the emergence of local markets, as the supply is uncertain and in inadequate volumes. Aggressive livestock production habits as overgrazing cause soil compaction and contributes to erosion, and decreases soil fertility, organic matter content and water infiltration and storage. Maintained organic food production then accelerates land degradation, hampers labor and land productivity and lowers food security. The low regional revenue realized under these circumstances slows down land productivity investments through procurement of nitrogen fertilizers and modern farm equipment. The resulting food supply in the rural areas concern naturally suffers from poor food security and low liquidity.

Initiatives to break this vicious circle of malfunctioning agricultural input and output markets, weak infrastructure and environmental destruction can be classed in three groups depending on which factor of the chain they primarily address; (i) Direct food support, often by foreign aid's organizations, is a temporary relief to avoid open famine and civil unrest; (ii) Improved land productivity programs aim at educating and equipping local farmers to used irrigation, mechanized production and optimal cropping techniques to increase the land yield and hence the food security; (iii) Market deregulation efforts and subsidies are indirectly providing incentives and means to farmers to sell their surplus and gradually invest in high-yield crops.

The first class of initiatives, direct intervention by a third party, is clearly detrimental. It provides the regions with a false sense of food security and would theoretically provide incentives to grow cash crops or aggressive deforestation. When it is applied, it is normally called for by humanitarian reasons and of fairly short duration. The second initiative is promoted among others by

the Foods and Agriculture Organization (FAO) and other United Nations' organs, prescribing governmental intervention in normative settings. By providing guidelines, studies and ready-made action plans, the idea is to achieve local change by higher level interaction, a top-down approach. However suitable this may be under certain circumstances and prerequisites, the approach is indeed ignoring some basic microeconomic behavioral rules of the individual low-level decision makers. Thus, if the governmental authority is not sufficient to enforce the resulting plan in its entirety, which in most applications would be the case, the predictive value of the indicators of economic and environmental status is likely to be very low. The planning approach thus ends up in a vacuum, neither modeling a normative scenario to be implemented, nor predicting an outcome given some conditions.

The third initiative, enforced by agencies as the International Monetary Fund (IMF) and USAID, is adopting a market-oriented view to solve the long-term problem. The incentives are many times very convincing, such as the approval of loans for infra-structure investments and long-term financial support. However, the achieved results, improved markets and removal of restrictions and subsidies, will not necessarily lead to a sustainable development. Short-term gains may be realized in open markets by heavy cultivation of cash-crops close to infra-structure and market places, in particular in scenarios where land-prices are low due to an under-developed real estate market. Further, regional and governmental planning may become difficult and reactive rather than pro-active in the absence of good predictors of market behavior.

This paper argues for an alternative approach which conserves the bounded micro-economic rationality of the agents but still enables a regional or governmental decision maker to experiment with economic decision variables to promote a desired agricultural development. We present a case where an existing multi-criteria land-use model for the FAO Agro-Ecological Zones (AEZ) approach can be used even in a more elaborate market setting. The outlined model operates with price subsidies as decision variables, rather than the actual land-usage. The intended local decision maker may use the system to estimate the economic impact of various subsistence and environmental concerns related to the predicted land-use. The mathematical formulation of the model lends itself to decomposition algorithms and thus to interesting sub-problems for each market.

The outline of the paper is as follows. First, an introduction is given to the market-oriented approach. Next, the Kenya AEZ model (Agrell *et al.*, 1997) is reviewed, later to be reformulated in the proposed way. A few concluding remarks end the presentation.

In this context, producer subsidies are seen exclusively as a mean to achieve a desired argo-ecological development and any discussion regarding the effects on income distribution and regional development is omitted. By making the subsidies dependent on goods marketed the controllability improves and this naturally creates an incentive to market surplus production. To be more exact, assume the existence of markets $g = 1, \dots, G$ where crops and livestock products $i = 1, \dots, N$ potentially are marketed. For each good i and market g , there exists a demand function, $D_{ig}(p_{ig})$ measured in calories,

$$D_{ig}(p_{ig}) = \xi_{ig} - \eta_{ig} p_{ig}, \quad (1)$$

where ξ_{ig} is a constant, p_{ig} is the price per calorie of i , and η_{ig} is the price elasticity with respect to the food item. If no price differentiation over markets is desired or possible, the index g may be omitted for the price term. Assuming profit maximization under zero costs or revenue maximization, the optimal price p_{ig}^* is given by,

$$p_{ig}^* = \frac{\xi_{ig}}{2\eta_{ig}}. \quad (2)$$

When calculating the market subsidy P_{ig} , it is seen as a producer incentive without impact on the parameters of the Leontief production function, $\phi(\mathbf{x}) \in \mathbb{R}^N$. Assume that the net producer profit of each good is c_i , collected in the vector $\mathbf{c} \in \mathbb{R}^N$. Thus, the farmer(s) solves the profit maximization problem [FPM] in each period for the decision vector $\mathbf{x} \in X$.

$$[\text{FPM}] \quad \mathbf{x}^0 = \arg \max_{\mathbf{x} \in X} \Pi = \mathbf{c}^T \phi(\mathbf{x}) \quad (3)$$

[FPM] implies a production $\mathbf{D}^0 = \phi(\mathbf{x}^0)$, which may not be ecologically or long-term socially acceptable. E.g., deforestation to grow a few harvests of coffee on a mountain slope is maximizing the farmer's profit objective, but undermining the economical and ecological sustainability of the area. The central planner also faces criteria such as gross food output, food output under poor conditions, usage of arable land, self-sustainability, erosion and maximum cell erosion. Thus, the central planner faces the problem of maximizing some other criterion $z_k = \mathbf{b}_k^T \mathbf{x}$ defined on the producers decision variables, [Ck]. These latter criteria will be defined and explained in further detail below.

$$[\text{Ck}] \quad \tilde{\mathbf{x}}^k = \arg \max_{\mathbf{x} \in X} z_k = \mathbf{b}_k^T \mathbf{x} \quad (4)$$

The desirable production is thus $\tilde{\mathbf{D}} = \phi(\tilde{\mathbf{x}})$, which cannot directly be stipulated in a market economy with low ability and willingness to enforce regulations regarding rural agricultural production. Rather, we intend to find a system a subsidies, $\mathbf{P} \in \mathbb{R}^N$, for each market, such that the $\tilde{\mathbf{D}} = \phi(\tilde{\mathbf{x}})$,

$$[\text{FSM}] \quad \tilde{\mathbf{x}} = \arg \max_{\mathbf{x} \in X} \Pi(\mathbf{P}) = (\mathbf{P} + \mathbf{c})\phi(\mathbf{x}). \quad (5)$$

Note that the resulting model is a quadratic program in objective (5). However, this is circumvented by first studying the cost of these subsidies, $\mathcal{J}(\mathbf{x})$, which in equilibrium has to be

$$\mathcal{J}(\tilde{\mathbf{x}}) = \Pi^0 - \Pi(\tilde{\mathbf{x}}) = \mathbf{c}^T \phi(\mathbf{x}^0 - \tilde{\mathbf{x}}). \quad (6)$$

Thus, since the subsidies *per se* are of no interest to the decision maker, it is sufficient to run the LP model with a mathematically redundant criterion, $\mathcal{J}(\mathbf{x})$, to negotiate the maximum level of subsidies in relation to achieved levels of other criteria. When a final result \mathbf{x}' , $\phi(\mathbf{x}')$, Π' is obtained, the central planner solves a decomposition problem of the Dantzig-Wolfe type, where the available subsidies, \mathcal{J} , and the attained criteria levels, $\tilde{z}_1, \dots, \tilde{z}_k$, form the central constraints and the sub units (the farms) answer by profit maximization. Notice that non-activity has a given price in the subsidy system, as i.e. certain ecologically sensitive areas may be given area-based subsidies for fallow. The idea behind the decomposition is to generate extreme points \mathbf{y} , through the sub problems and find the optimal solution to the master problem as a convex combination of extreme points, $\mathbf{Y}\lambda$. The space allotted does not allow a detailed discussion of multi-criteria decomposition and the reader is referred to Bogetoft and Tind (1990) and Bogetoft *et al.* (1994).

The master problem [M], corresponding the central planner, is to maximize the weighted value of the criteria \mathbf{z} subject to a common resource constraint in terms of the subsidies. The central constraints form a non-empty matrix \mathbf{A} where the top row are the sum of all products with market prices.

$$[\text{M}] \quad \max_{\lambda} \mu \mathbf{H} \mathbf{Y} \lambda \quad (7)$$

$$\text{s.t.} \quad \mathbf{A} \mathbf{Y} \lambda \leq \mathbf{a} \quad (8)$$

$$\lambda^T \mathbf{1} = 1 \quad (9)$$

$$\lambda \in \mathbb{R}_+^M \quad (10)$$

The sum of the convex combination multipliers λ must be one and the size of \mathbf{Y} , the matrix of found extreme points has M vectors. Denote an optimal solution to [M] by λ^* and let w^* be the associated dual price with the first row

of (8) and α^* the dual variable for (9). Given these latter dual variables, each market solves its sub problem [SUB], where \mathbf{B} is the matrix of all farm-level constraints and \mathbf{b} the corresponding vector of farm-level resources.

$$[\text{SUB}] \quad \max_{\mathbf{x}} (\mathbf{c}^T - \mathbf{w}^* \mathbf{A}) \mathbf{x} \quad (11)$$

$$\text{s.t.} \quad \mathbf{B} \mathbf{x} \leq \mathbf{b} \quad (12)$$

$$\mathbf{x} \geq 0 \quad (13)$$

If the reduced costs for [SUB] are positive, i.e.,

$$(\mathbf{c}^T - \mathbf{w}^* \mathbf{A}) \mathbf{x}^* - \alpha^* > 0 \quad (14)$$

then the obtained solution from [SUB] is included in \mathbf{Y} and [M] is resolved. If they are non-positive, the procedure stops as [M] cannot be improved. The procedure converges to a point $\mathbf{x}' = \mathbf{Y} \lambda'$ which is optimal with respect to the instrument of control. Since the number of extreme points is finite, the procedure converges after a finite number of steps. The price subsidies are given as the share of the common resource S allotted to market g and product i in [M].

THE BUNGOMA DISTRICT IN KENYA

Kenya is chosen as an example of this initiative, a developing country exhibiting rapid population growth, a relatively open economy and a traditional dependency on export of agricultural goods such as coffee, cotton and sugar cane. Currently, Kenya has about 2 million farm holders, with a typical lot size ranging from 2 ha to 15 ha. Given a steady population growth rate of 3% annually (UN, 1997) and a weak economy suffering from high inflation that soared to 29% in 1994 (IMF, 1995), the need for an accurate regional planning strategy is apparent. Deforestation is accelerating, causing serious environmental problems, and the dependence on rainfall for natural irrigation renders the entire support system vulnerable. Irrigation in Kenya only accounts for less than 2% of the cultivated land. In the short-term, the challenge is to assure adequate support for the growing population and to maximize agricultural exports, while the long-term strategy is to ensure sustainability by preserving an ecological balance and attaining a satisfactory long-term growth in national income.

The Bungoma district, located along the foot hills of Mt. Elgon in West Kenya, serves as a good example of the conflicting goals and objectives inherent to land use management. The district is quite suitable for agricultural activity, as about 222,000 of the total area of 319,300 ha are arable. The district's rich soil, plentiful and well-distributed rainfall and a fairly long growing

season (270 days) allow for a wide variety of different agricultural crops. In addition to the current cereal production of maize, wheat, barley and finger millet, the region is well set for cassava, beans and potatoes, not to mention cash crops such as coffee, tea and pyrethrum (Fischer and Antoine, 1994). The population is growing rapidly, from about 679,000 in the 1989 census to a projected 920,000 in 2000. The challenge for the local development committee is to improve the productivity level of the agriculture to cope with the boom, simultaneously considering the economical growth of the area and the need to stall deforestation and other adverse ecological effects of intensified farming.

The original model by Agrell *et al.* (1997), which draws upon a long-term collaboration between the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA) (FAO, 1981, 1984; FAO/IIASA, 1991, 1993a), is intended as an agro-ecological decision support system for regional planning on site (Fischer and Antoine, 1994). The underlying methodology, the Agro-Ecological Zones (AEZ) was developed in 1976 by a collaboration between FAO and IIASA (FAO, 1981, 1991a, 1993). AEZ provides decision support for various problem related to land use appraisal for planning sustainable agricultural development. Before the application to Kenya (FAO/IIASA, 1991), the methodology has been used in land use assessments in Bangladesh, China, Mozambique, Nepal, Nigeria, the Philippines, and Thailand.

MODEL FORMULATION

The original model (FAO/IIASA, 1993) optimizes a single criterion, although in the documentation five different objectives are suggested for separate optimization. In Agrell *et al.* (1997) this model is enhanced by multiple decision criteria and an interactive methodology to solve these in the AEZ framework. This paper forwards the reasoning by proposing a market-oriented formulation, a quadratic program which also includes the cost of market establishment as one criterion. For a further description of the constraints and the defined terms, cf. Agrell *et al.* (1997). The land use allocation decision process essentially involves determining the appropriate share of each crop, the appropriate allocation of livestock and the best way to feed the livestock with available crops, crop residues and by-products, and grass. Hence, the model includes four groups of decision variables, the price subsidies P_{ig} of crop i in market g , the land use shares x_{kj} of cropping activity k in each cell j , the number of livestock units L_{rs} of livestock system s kept in livestock zone z , and the feed ration f_{itrs} in period (season) t of feed item l from crop i allocated to livestock system s in livestock zone z .

The AEZ database (FAO/IIASA, 1993b) contains detailed information on 64 food and cash crop types, pastures, 31 fuelwood species and 10 livestock systems. The AEZ model includes 36 commodities, of which 26 are crop and 10 are livestock production commodities, and divides Kenya into a grid of 90,000 agro-ecological cells. Each cell is assumed reasonably homogeneous in terms of the relevant characteristics and is assigned to one or more cropping, livestock and market zones.

As an intermediate variable, introduce, a_{ijk} , as the area of cell j in which crop i is harvested as part of cropping activity k in cell j ,

$$a_{ijk} = x_{kj} g_{ik} E_j c_{kj}, \text{ for all } i, k, j, \quad (15)$$

where E_j is the size (surface) of cell j , c_{kj} is the cultivation factor for cropping activity k in cell j and g_{ik} represents the proportion of crop i in activity k . Note that crop activity k includes both simple and multiple sequential crop combinations, so that several crops i may belong to a given crop combination.

We propose seven relevant decision criteria to capture the decision with the regional development committee as the intended user. The criteria are derived from the stated focus of the regional committee to assure the food sustainability in the region during varying hydrological regimes, to induce productivity improvements in the agricultural sector, to promote the local economy, and to protect ecological values through positive advice and collaboration with the rural population. As argued above, one possible mean to achieve this development is producer subsidies, which are to be financed by either the Kenyan government or foreign aids organizations. The amount of subsidies is to be minimized, which forms the first objective SUBSID. The food criteria are FOOD, for total annual food production, and FOODL, for the minimal expected annual food production. The self-sufficiency is expressed through one criterion, SSR. The net revenue realized by the local farmers, NETREV, measures the economic objective. The ecological interests are met through a criterion for total annual soil loss due to erosion, EROS, and a criterion for maximum annual soil loss in any cell, EROSMX. Next, we define these criteria mathematically.

The SUBSID criterion measures the expected annual cost of producers subsidies (in 10^6 Kenyan Shillings) given the market assumptions above.

The first (FOOD) simply maximizes the total annual net food production (in billion kcal), whereas the second (FOODL, also in billion kcal) takes different moisture regimes into account, in order to assess the stability of the plan during years of draught and threatening famine. FOOD expresses the net

annual calories made available through agricultural production. Specifically, FOOD in (2) measures food output as the net weighted sum of converted and processed food energy and protein available for human consumption. The first term in (16) applies to crop production, the second to livestock production.,

$$\text{FOOD} = \sum_{j=1}^J \sum_{i=1}^N \sum_{k=1}^K \sum_{t=1}^T \kappa_i \varepsilon_i (1 - w_i) y_{ikj} a_{ikj} d_{ikt} + \sum_{b=1}^H \sum_{i \in N_b} \sum_{z=1}^Z \sum_{s=1}^S \kappa_i \varepsilon_i (1 - w_i) y_{is} L_{sz} \quad (16)$$

where $y_{ikj} a_{ikj}$ represents the gross production of crop i , cropping activity k , cell j , y_{is} is the output of livestock product i per reference livestock unit (RLSU) of livestock system s , L_{sz} is the number of RLSU of system s in livestock zone z , so that $y_{is} L_{sz}$ is the gross production of livestock product i per RLSU of livestock system s , zone z , w_i is the production waste proportion of crop i , κ_i is the calorie content per unit of food item i , ε_i is the extraction rate, i.e., the conversion rate of produce of crop/livestock product i to food product i , d_{ikt} is the share of production from crop i as part of activity k harvested in season t , N_b is the index set of crops that belong to crop group b .

FOODL is similar to FOOD, but the coefficients y_{ikj}^s and y_{is}^s in (3) correspond to yields under severe climactic conditions, rather than average or good,

$$\text{FOODL} = \sum_{j=1}^J \sum_{i=1}^N \sum_{k=1}^K \sum_{t=1}^T \kappa_i \varepsilon_i (1 - w_i) y_{ikj}^s a_{ikj} d_{ikt} + \sum_{b=1}^H \sum_{i \in N_b} \sum_{z=1}^Z \sum_{s=1}^S \kappa_i \varepsilon_i (1 - w_i) y_{is}^s L_{sz} \quad (17)$$

where $a_{ikj} y_{ikj}^s$ is the gross production under severe climactic conditions of crop i , cropping activity k , cell j , y_{is}^s is the output under severe climactic conditions of livestock product i per reference livestock unit (RSLU) of livestock system s , all other constants are as in (16).

One of Kenya's most important strategic objectives is to maintain a high level of food self-reliance. The self-sufficiency ratio SSR, stated mathematically in (18), measures the extent to which broad commodity groups (e.g., cereals, root crops, meats) are produced within the Bungoma region. SSR maximizes the minimum self-sufficiency ratio across all crop commodity groups $b \in H_C$ and livestock commodities $b \in H_L$, so that the 'worst' value is maximized. H_C is the index set of crop commodities, and H_L is the index set of livestock com-

modities. The effect of this criterion is to balance the production mix to assure local resiliency and relieve the underdeveloped infrastructure.

$$SSR = \min_b \left\{ \begin{array}{l} \frac{1}{D_b} \sum_{i \in N_b} \sum_{k=1}^K \sum_{j=1}^J \sum_{t=1}^T \varepsilon_i (1 - w_i) y_{ikj} a_{ikj} d_{ikt} : \quad \forall b \in H_C, \\ \frac{1}{D_b} \sum_{i \in N_b} \sum_{s=1}^S \sum_{z=1}^Z \varepsilon_i (1 - w_i) y_{is} L_{sz} : \quad \forall b \in H_L. \end{array} \right\}, \quad (18)$$

where D_b is the demand target (in 10^9 kcal) for commodity group b and the other parameters are as defined above.

The NETREV criterion in (19) expresses the expected net revenue (in 10^6 Kenyan Shillings, KSh) resulting from the planning decision, as the difference between the expected gross value of the production and the expected production cost,

$$\begin{aligned} \text{NETREV} = & \sum_{i=1}^N \sum_{j=1}^J \sum_{k=1}^K \left[(1 - w_i) p_{ikj} y_{ikj} - \sum_{m=1}^M c_m v_{ikjm} \right] a_{ikj} \\ & + \sum_{b=1}^H \sum_{i \in N_b} \sum_{s=1}^S \sum_{z=1}^Z \left[(1 - w_i) p_{is} y_{is} - \sum_{m=1}^M c_m v_{ism} \right] L_{sz} \end{aligned} \quad (19)$$

where p_{ikj} and p_{is} are the per calorie price of crop produce of crop i , cropping activity k , cell j and livestock product i from livestock system s , c_m is the cost/weight per unit of production input m , v_{ikjm} is the amount of input type m required per ha of crop i cultivated as part of activity k in cell j , and v_{ism} is the amount of input type m required per RLSU of livestock system s .

The subsidies maximal budget is calculated as (6), i.e.,

$$\text{SUBSID} = \text{NETREV}^* - \text{NETREV} \quad (20)$$

Where NETREV^* denotes the unconstrained profit maximum.

The two cell erosion criteria, EROS and EROSMX, are important means to assess the environmental impact of agricultural production. Whereas EROS minimizes the total soil loss (in 10^3 tons of soil per year) for all cells in the region combined, EROSMX minimizes the worst (i.e., maximum) soil loss (in tons per ha per year) in any cell used for agriculture. These erosion measures provide information about the long-term agro-ecological sustainability of the proposed production plan. EROS and EROSMX also complement the economic information by supplying the downside of extensive mono-cropping of cash crops, which is very rewarding economically. The expected soil loss per ha and year in cell j from activity k is estimated by e_{kj} , so that EROS and EROSMX can be expressed as (21) and (22), respectively,

$$\text{EROS} = \sum_{k=1}^K \sum_{j=1}^J e_{kj} x_{kj} E_j, \quad (21)$$

$$\text{EROSMX} = \max_j \left\{ \sum_{k=1}^K e_{kj} x_{kj} \right\}. \quad (22)$$

THE CONSTRAINT SET

The pre-established upper (UA_b) and lower (LA_b) bounds in (23)-(24) restrict the harvested areas dedicated to each commodity group $b \in H$ to pre-determined levels,

$$\sum_{i \in N_b} \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \leq UA_b, \quad b = 1, \dots, H, \quad (23)$$

$$\sum_{i \in N_b} \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \geq LA_b, \quad b = 1, \dots, H. \quad (24)$$

Similarly, in order to allow for reasonable non-agricultural land use, housing and infrastructure, game parks and forestry, the total arable land is limited by the upper bound TA , as in (25),

$$\sum_{k=1}^K \sum_{j=1}^J x_{kj} E_j \leq TA. \quad (25)$$

The distribution of land across crop groups is controlled by imposing upper and lower bounds on the harvested area for each crop group N_b , determined as crop group-specific lower ($L\rho_b$) and upper ($U\rho_b$) bounds on the share of total arable land, as in (26)-(27).

$$\sum_{i \in N_b} \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \leq U\rho_b \sum_{i=1}^N \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \quad (26)$$

$$\sum_{i \in N_b} \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \geq L\rho_b \sum_{i=1}^N \sum_{k=1}^K \sum_{j=1}^J a_{ikj} \quad (27)$$

Specific group-specific food demand requirements for each livestock commodity are included in the model through the upper (UD_b) and lower (LD_b) bounds in (28)-(29), where b is a livestock commodity in the set H_l .

$$\sum_{i \in N_b} \sum_{s=1}^S \sum_{z=1}^Z \varepsilon_i (1 - w_i) y_{is} L_{sz} \leq UD_b, \quad \text{for each } b \in H_L \quad (28)$$

$$\sum_{i \in N_b} \sum_{s=1}^S \sum_{z=1}^Z \varepsilon_i (1 - w_i) y_{is} L_{sz} \geq LD_b, \quad \text{for each } b \in H_L \quad (29)$$

The ratio of calories to proteins from food products is regulated by constraints to assure an acceptable balanced diet regardless of policy in each climactic region r . In (30), CAL is the maximum calorie/protein ratio for human consumption, C_r is the set of agro-ecological cells in region r , Z_r is the set of livestock zones in region r , π_i is the protein content per unit of food item i , and the other parameters are as in (16).

$$\sum_{i=1}^N \kappa_i \varepsilon_i (1 - w_i) \left(\sum_{j \in C_r} \sum_{t=1}^T y_{ikj} a_{ikj} d_{ikl} + \sum_{z \in Z_r} \sum_{s=1}^S y_{is} L_{sz} \right) \leq$$

$$CAL \sum_{i=1}^N \pi_i \varepsilon_i (1 - w_i) \left(\sum_{j \in C_r} \sum_{t=1}^T y_{ikj} a_{ikj} d_{ikl} + \sum_{z \in Z_r} \sum_{s=1}^S y_{is} L_{sz} \right), \quad r = 1, \dots, R. \quad (30)$$

To ensure that the animal feed consumption does not exceed the feed supply, aggregate feed availability constraints are imposed for every feed item in each livestock zone. These constraints dynamically connect the decision variables x_{kj} , the level of cropping activity k in cell j , and f_{illz} , the amount of feed item l from crop i allocated to livestock system s in season t and livestock zone z . To make the model structure more transparent, first two auxiliary variables are defined, the net production F_{illz} of feed item l (in dry matter) from crop i in season t and livestock zone z , and, the supply FS_{illz} of feed item l (in dry matter) from crop i in season t and livestock zone z . These entities are defined in (31)-(33),

$$F_{illz} = u_{ill} r_{ill} \sum_{j \in C_z} \sum_{k=1}^K y_{ikj} a_{ikj} d_{ikl}, \quad \begin{cases} i = 1, \dots, N; l = 1, \dots, L, \\ t = 1, \dots, T; z = 1, \dots, Z. \end{cases} \quad (31)$$

where r_{ill} is the production of feed item l from activity k relative to the production of primary produce of crop i , u_{ill} is the feed utilization factor of crop i , feed item l , in season t . The initial feed supply is given by (33),

$$FS_{illz} = F_{illz}, \quad t = 1, \quad (32)$$

For all succeeding periods t , the feed supply $FS_{il,tz}$ is defined as in (34), where μ_{il} is the feed depreciation factor related to carry-over of feed supplies from crop i , item l from season $t-1$ into season t .

$$FS_{il,tz} = F_{il,tz} + (1 - \mu_{il}) \left(FS_{il,t-1,z} - \sum_{s=1}^S f_{il,t-1,zs} \right), \quad (33)$$

$$i = 1, \dots, N; l = 1, \dots, L; t = 2, \dots, T; z = 1, \dots, Z,$$

Where $f_{il,tz}$ represents the feed use from crop i , feed item l , allocated to livestock system s in season t , in livestock zone z . The set of aggregate feed consumption constraints on feed item l , for any crop i , by the livestock in zone z in period t is presented in (34),

$$\sum_{s=1}^S f_{il,tz} \leq FS_{il,tz}, \quad \begin{cases} i = 1, \dots, N; l = 1, \dots, L, \\ t = 1, \dots, T; z = 1, \dots, Z. \end{cases} \quad (34)$$

The seasonal feed constraints assure that seasonal feed intake in all livestock systems and zones is within an acceptable range and that the total annual intake does not fall below average annual requirements. These constraints force a realistic distribution of the feed over time, rather than assuming that infinite quantities of feed can be stored for any length of time. The seasonal crude protein feed quality constraints are analogous to the seasonal feed constraints, and restrict the seasonal and annual intake of digestible crude protein. For further detail, cf. Agrell *et al.* (1997).

In order to prevent dramatic re-distributions of livestock types within each zone, to accommodate historical conditions and model adjustment speed, (35) and (36) constrain the number of livestock units to a pre-defined fraction of the total livestock in the zone. Let $U\beta_{rz}$ and $L\beta_{rz}$ be the maximum and minimum share of livestock system s supported in livestock zone z , respectively.

$$L_{rz} \leq U\beta_{rz} \sum_{s=1}^S L_{sz}, \quad s = 1, \dots, S; z = 1, \dots, Z \quad (35)$$

$$L_{rz} \geq L\beta_{rz} \sum_{s=1}^S L_{sz}, \quad s = 1, \dots, S; z = 1, \dots, Z \quad (36)$$

A similar condition regulates the proportions between livestock systems in each broad climactic region. The proportion of animals (expressed as reference livestock system units, RLSU) in each region is restricted to a given fraction of the total livestock in the region. The climatic regions r are defined

in terms of groups of length-of-growing period (LGP) zones, e.g., the sub-humid zone consists of all land with LGP values between 180 and 270 days.

$$\sum_{z \in Z_r} L_{sz} \leq U\alpha_r \sum_{s=1}^S \sum_{z \in Z_r} L_{sz}, \quad s = 1, \dots, S; r = 1, \dots, R, \quad (37)$$

where $U\alpha_r$ is the maximum share of livestock unit s in region r supported in relation to the total number of livestock units. In (38), $L\alpha_r$ denotes the minimum share of livestock unit s in region r supported in relation to the total numbers of livestock units.

$$\sum_{z \in Z_r} L_{sz} \geq L\alpha_r \sum_{s=1}^S \sum_{z \in Z_r} L_{sz}, \quad s = 1, \dots, S; r = 1, \dots, R, \quad (38)$$

The resources needed for crop and livestock production are limited to the supply V_m of resource m (e.g., power, capital, fertilizer, labor) in the region. The constraints in (39) establish separate upper bounds for each resource m . On the left-hand side of (39), v_{ijkm} represents the input requirement of input m per ha of crop i cultivated through activity k in cell j , and v_{sm} is the input requirement of input m per RLSU of livestock system s . The input coefficients v_{sm} of those activities that generate resources, e.g., draught power and manure from animals are negative.

$$\sum_{j=1}^J \sum_{k=1}^K \sum_{i=1}^N v_{ijkm} a_{ijk} + \sum_{s=1}^S \sum_{z=1}^Z v_{sm} L_{sz} \leq V_m, \quad m = 1, \dots, M. \quad (39)$$

Each cropping activity x_{kj} in cell j has a nonnegative share, and the sum of all activity shares in cell j in (40) equals at most unity. As non-activity is an option, (40) is expressed as an inequality. Moreover, in order to prevent an overly skewed crop mix, most individual cropping activities in cell j cannot take more than a share $u x_j$, implying the constraint set in (41). In specific cases, the limitation in (41) is waived, e.g., for specific perennial crops, environmentally compatible cropping activities such as beans, forage legumes and grasses, and cells with only one suitable activity (Fischer and Antoine, 1994).

$$\sum_{k=1}^K x_{kj} \leq 1, \quad j = 1, \dots, J, \quad (40)$$

$$x_{kj} \leq u x_j, \quad k = 1, \dots, K; j = 1, \dots, J, \quad (41)$$

Finally, non-negativity applies to all decision variables, x_{kj} , L_{sz} and f_{illz} :

$$x_{kj}, L_{sz}, f_{illsz} \geq 0, \quad \begin{cases} i = 1, \dots, N; j = 1, \dots, J; \\ k = 1, \dots, K; l = 1, \dots, L; \\ s = 1, \dots, S; t = 1, \dots, T; \\ z = 1, \dots, Z. \end{cases} \quad (42)$$

To model the risk aversion at cell level in presence of weak sustainability conditions, an additional set of risk constraints are implemented as follows. First, disaggregate (17) to the cell level cropping output FOODL_j (in billion kcal) as in (43) below.

$$\text{FOODL}_j = \sum_{i=1}^N \sum_{k=1}^K \kappa_i \varepsilon_i (1 - w_i) y^s_{ikj} a_{ikj} \quad (43)$$

For each cell j , let Fx_{ikj} be an optimal solution to the problem to maximize FOODL_j subject to constraints (23) through (42). From this information it is possible to determine the maximum possible food output in cell j under severe climactic conditions, $\text{MXF}_j = \text{FOODL}_j$. Analogously for value maximization, VALUEL_j in (44) expresses the expected value generated through cropping during severe conditions in cell j .

$$\text{VALUEL}_j = \sum_{i=1}^N \sum_{k=1}^K (1 - w_i) p_{ikj} y^s_{ikj} a_{ikj} \quad (44)$$

Now, let Vx_{ikj} and MXV_j be an optimal solution and the associated cell level objective function value, respectively. The risk constraints in (45) and (46) require that the crop combination selected in any cell must produce at least αMXF_j or αMXV_j , where the parameter α is empirically estimated. The risk constraints apply at the cell level, rather than the district level, because in the case of subsistence farming a particular household cannot take too high a risk of crop failure, although this might be better on average or in aggregate. The constraints are necessary due to the non-enforcing structure of the model and a rational micro-economic behavioral assumption on the farmers.

$$\sum_{i=1}^N \sum_{k=1}^K \kappa_i \varepsilon_i (1 - w_i) y^s_{ikj} a_{ikj} \geq \alpha \text{MXF}_j, \quad \text{for all } j = 1, \dots, J \quad (45)$$

$$\sum_{i=1}^N \sum_{k=1}^K (1 - w_i) p_{ikj} y^s_{ikj} a_{ikj} \geq \alpha \text{MXV}_j, \quad \text{for all } j = 1, \dots, J \quad (46)$$

AN INTERACTIVE MCDM APPROACH

Various multiobjective linear programming (MOLP) solution procedures have been developed (see, *e.g.*, Shin and Ravindran, 1991). We follow Agrell *et al.*

(1997) and select the Interactive Weighted Tchebycheff Procedure (IWTP) of Steuer and Choo (1983), due to its desirable mathematical and decision-support related properties. The IWTP is attractive computationally, since it can be implemented using existing commercial optimization software, since it is guaranteed to provide the decision maker with non-dominated solutions at all times, and since it is user-interactive and provides flexible decision-support for multi-criteria programming problems. The mode of operation is straightforward. First, the extreme points are assessed relative to the model to give attainable ranges of outcome, cf. Table 1. Second, an iteration commences where the algorithm samples and filters a sample of non-dominated solution and presents these to the decision maker. The decision maker chooses one or more as preferred and this information is used by the algorithm to contract the area of search. The iterations stop when the decision maker is completely satisfied and a most preferred solution has been obtained. Table 2 depicts the results from the current model with the preferences revealed in the final iteration of Agrell *et al.* (1997). The expert decision maker in this experiment preferred solution 1-5, which in our framework could have been implemented using a maximum of 269 million KSh producer subsidies. The method does not require the decision maker to converge to a final solution at a pre-determined rate, and a previously discarded solution can be reconsidered at any time, thus facilitating learning about the problem. The decision maker can also guide the solution process at any time by inserting bounds on the criteria. A comparative experimental study of interactive MOLP methods by Buchanan and Daellenbach (1987) found the IWTP to be favored over several competing methods, from the user's viewpoint. Not to burden the paper with excessive detail regarding the functionality of the method, the description of the ITWP is omitted and the reader is referred to, *e.g.*, Steuer and Choo (1983).

Table 1: The Initial Model Payoff Table (adapted from Agrell *et al.*, 1997).

Objective Criterion	<i>min</i> SUBSID	<i>max</i> NETREV	<i>Max</i> FOOD	<i>max</i> FOODL	<i>max</i> SSR	<i>min</i> EROS	<i>min</i> EROSMX	
<i>min</i> SUBSID	0	0	234	246	272	525	534	10 ⁶ KSh
<i>max</i> NETREV	1 317	1 317	1 083	1 071	1 045	792	783	10 ⁶ KSh
<i>max</i> FOOD	945	945	1 197	1 139	906	773	747	10 ⁹ kcal
<i>max</i> FOODL	732	732	970	1 010	654	599	575	10 ⁹ kcal
<i>max</i> SSR	80	80	96	86	107	32	32	%
<i>min</i> EROS	2 620	2 620	3 207	3 256	3 527	1 165	1 838	kton/ha
<i>min</i> EROSMX	85	85	113	148	228	29	12	ton/ha

Table 2: Final solution with current model (adapted from Agrell *et al.*, 1997).

Iteration 5	1-5	2-5	3-5	4-5	5-5	6-5	7-5	
<i>min</i> SUBSID	269	276	279	274	272	239	239	10 ⁶ KSh
<i>max</i> NETREV	1 048	1 041	1 038	1 043	1 045	1 078	1 078	10 ⁶ KSh
<i>max</i> FOOD	1 109	1 112	1 078	1 081	1 052	1 121	1 147	10 ⁹ kcal
<i>max</i> FOODL	880	894	858	851	824	889	924	10 ⁹ kcal
<i>max</i> SSR	99	99	100	100	100	98	97	%
<i>min</i> EROS	2 478	2 900	3 000	2 733	2 900	2 896	2 664	kton/ha
<i>min</i> EROSMX	35	35	35	35	30	40	39	ton/ha

CONCLUSION

Analyzing the many inherent socio-economic trade-offs resulting from regional agro-ecological planning is a challenging task for conventional optimizing techniques. The many incommensurable objectives may render useless any attempt to simplify the problem by using constraints. In this approach, we have proposed an augmented decomposition method to deal with the implementation problem of agricultural policies. By deconstructing the problem into an interactive LP and a batch-run decomposition problem, where the master problem is the assignment of subsidies and the deviation from stated trade-offs and the sub problems are the cells forming the local markets. The approach, based on the Agro-Ecological Zones (AEZ) model (FAO, 1982) and the Steuer and Choo (1983) method, does not require any prior knowledge of decision analysis from the user. The operation is natural and supports a gradual exploration of the non-dominated surface, with improved acceptance and trust in the outcome as an added benefit (Buchanan and Daellenbach, 1987). The decision maker receives an integrated assessment of ecological, technological, social, demographic and economic aspect pertaining the appraisal of land resources of the Bungoma district in Kenya. The decision support is rich in detail for agro-economical land-use, including multi-cropping, livestock and crop sector integration, fuelwood production and soil erosion impact. The paper is a first step towards a more economically based agro-ecological policymaking, less focused at the theoretical goals and potential of production and with emphasis placed at the instruments to achieve a desired development. Further research will apply the approach to the Bungoma data, implement the approach computationally and test the decision making phase with expert and lay decision makers.

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