Multi-Attribute Modelling of Economic and Ecological Impacts of Cropping Systems

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Modelling of economic and ecological impacts of genetically modified crops is a demanding task. We present some preliminary attempts made for the purpose of the ECOGEN project "Soil ecological and economic evaluation of genetically modified crops". One of the goals of the project is to develop a computer-based decision support system for the assessment of economic and ecological impacts of using genetically modified crops, with special emphasis on soil biology and ecology. The decision support system will be based on a rule-based model incorporating both economic and ecological criteria. In this paper we present some preliminary results of developing the integral model and describe four specific sub-models. The first two sub-models are concerned with ecology and assess the ecological impacts of various types of weed and pest control, respectively. The other two sub-models assess the economic impacts of cropping systems at the farm and regional level, respectively. All the models were developed using a qualitative multi-attribute modelling methodology, supported by the software tool DEXi.

Povzetek: članek opisuje modeliranje ekoloških problemov kmetijstva.

1 Introduction

The possible use of genetically modified (GM) plants in agriculture needs in-depth investigations of ecological and economic consequences [1,2]. The investigations are important for both the European Commision (EC), who needs specifications for GM-plant risk assessment, and to farmers and the public who are concerned about the possible ecological and economic implications. Crop production involves complex decision-making processes, which require and justify the application of decision support systems [3].

The ECOGEN project [2] (*Soil ecological and economic evaluation of genetically modified crops*) is an EC-funded project aimed at combining simple lab tests, studies of multi-species model ecosystems, and field studies to acquire mechanistic and realistic knowledge about economic and ecological impacts of GM crops on the soil. Economic trade-offs are assessed and related to ecological effects. The economic and ecological knowledge gained in ECOGEN will be combined into a rule based model for a decision support tool.

The goals of the ECOGEN project are to:

1. Provide ecological and economical assessment and comparison of integrated cropping systems using GM or conventional crops, respectively.
2. Provide an ecological risk assessment of a GM cropping system and a conventional cropping system for the soil ecosystem based on single species tests, multispecies tests and long-term field investigations.
3. Adapt existing ecotoxicity testing tools to GM plant material and validate their use.
4. Provide economic assessment of GM crops and conventional crops with respect to a quantification of the expected trade-offs between the two and the implications for the EU Agriculture Policy.

Finally, we wish to incorporate ecological knowledge from single species tests, multispecies tests, and field investigations, as well as economic information from farming practices into a *rule-based model* to be used for predictions of economic decision-making processes and ecosystem behaviour.

In this paper, we present our preliminary attempts at this kind of modelling. We describe four qualitative multi-attribute models. Two of these models assess the ecological impacts of using various cropping systems that differ in the applied weed-control and pest control mechanisms, respectively. The other two models assess the economic impacts of cropping systems; these are assessed at farm and regional level, respectively.

2 Methodology

The goal of the project is to build an integrated rule-based model for assessing the sustainability of farming (GM and non-GM) taking into account ecological and economic aspects. On the ecological side, this includes a model of the impact of GM crops and pesticides on non-target organism and soil functions. The model will be hierarchically structured, with submodels for different aspects, e.g., a submodel for economic (ECONOMY) and a submodel for ecological (ECOLOGY) aspects. In general, then, the approach will involve the following components (Figure 1):

1. *Cropping systems*: Input items assessed by the model. Each cropping system is described by a vector of values, such as: crop type (e.g., corn), soil preparation (e.g., type of tillage), weed control (e.g., use of herbicides), pest control (e.g., use of pesticides), type and quantity of fertilization, soil characteristics, climate characteristics, economic indicators (e.g., involved yields and variable costs).
2. *Multi-attribute model*: A model that aggregates the characteristics of cropping systems into overall ecological and economic evaluations.
3. *Outputs*: Two assessments are obtained for each cropping system: ecological and economic impacts.

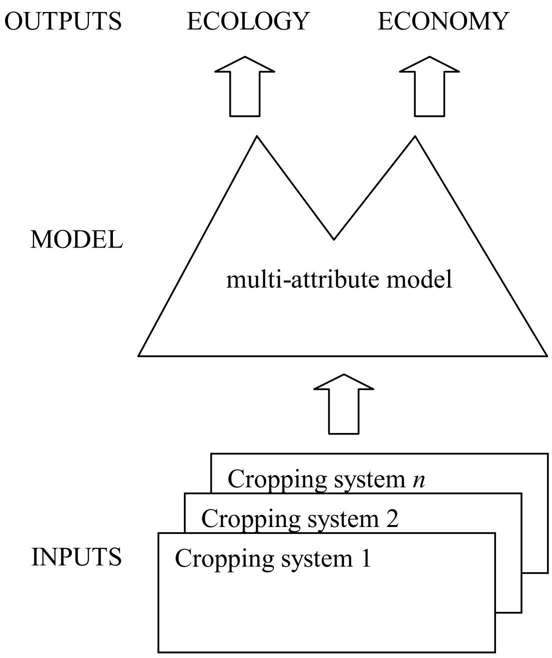

Figure 1: A general approach to multi-attribute assessment of cropping systems.

Using this schema, it will be possible to evaluate each cropping system and its impacts for several consecutive years, basically obtaining a chart as sketched in Figure 2. In addition, the model will facilitate all analyses and reports typically available in multi-attribute modeling [4,5]: what-if analysis, sensitivity analysis, simulation, selective explanation, and various visualizations.

The integral multi-attribute model will be mainly rule-based and will contain further submodels, which will be both qualitative (using rules) and quantitative (numerical/equations). They will be developed by the soil biology experts in the respective subareas, and in intensive interaction and collaboration with the decision support/data analysis experts. Decision support methods that rely on manual knowledge acquisition from domain experts will be used to elicit existing knowledge. Techniques from the area of multi-attribute decision-making and support will be used to support the construction of the overall model.

Where enough data are available, some submodels will be generated in a (semi)automated fashion by data analysis. In particular, machine learning techniques will be used to construct some submodels by analysing available data. Some sub-models of this type have already been developed in this way [6].

Reasoning with the rule-based model for decision support is crisp by default, but can be extended to fuzzy reasoning with moderate effort.

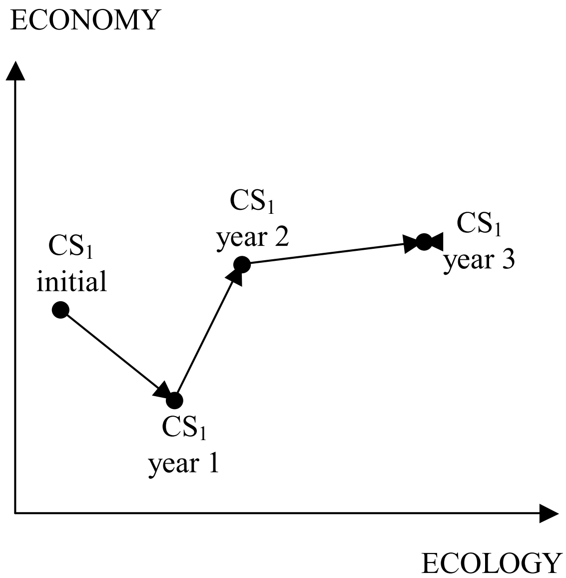

Figure 2: An example assessment of a cropping system CS1 through three consecutive years.

So far, we have developed two models for the ecological assessment of cropping systems, dealing with weed-control and pest-control mechanisms, respectively. These are described in section 3. In addition, we have developed two models for the assessment of economic impacts of cropping systems. The first model assesses the impacts at the farm level. The second model is an extension and adaptation of the

first one so as to assess the economic impacts at the regional level. These are presented later in section 4.
All these models are hierarchical, qualitative and multi-attribute. Thus, they are characterised by the following [4]:

- Each model consists of a number of hierarchically structured variables called *attributes*.
- Terminal nodes of the hierarchy *represent input attributes*; each cropping system is described by a vector of values of input attributes.
- Input attributes are aggregated through several levels of *aggregate attributes* into the overall assessment, which is represented by a single *root attribute*.
- All the attributes in the model are *qualitative*, meaning that they take symbolic values, described by words.
- The aggregation of values in the model is defined by *rules*.

The models were developed using the software tool DEXi [7]. DEXi facilitates the development of a tree of attributes, definition of aggregation rules (e.g., see Figure 4), evaluation of options (cropping systems in this case), what-if analysis and charting.

3 Ecological assessment

3.1 Weed-control model

With this model, cropping systems are assessed qualitatively using the five-value ordered scale: preferrable, acceptable, regular, poor, unacceptable. The model is hierarchical and has the structure of attributes as shown in Figure 3.

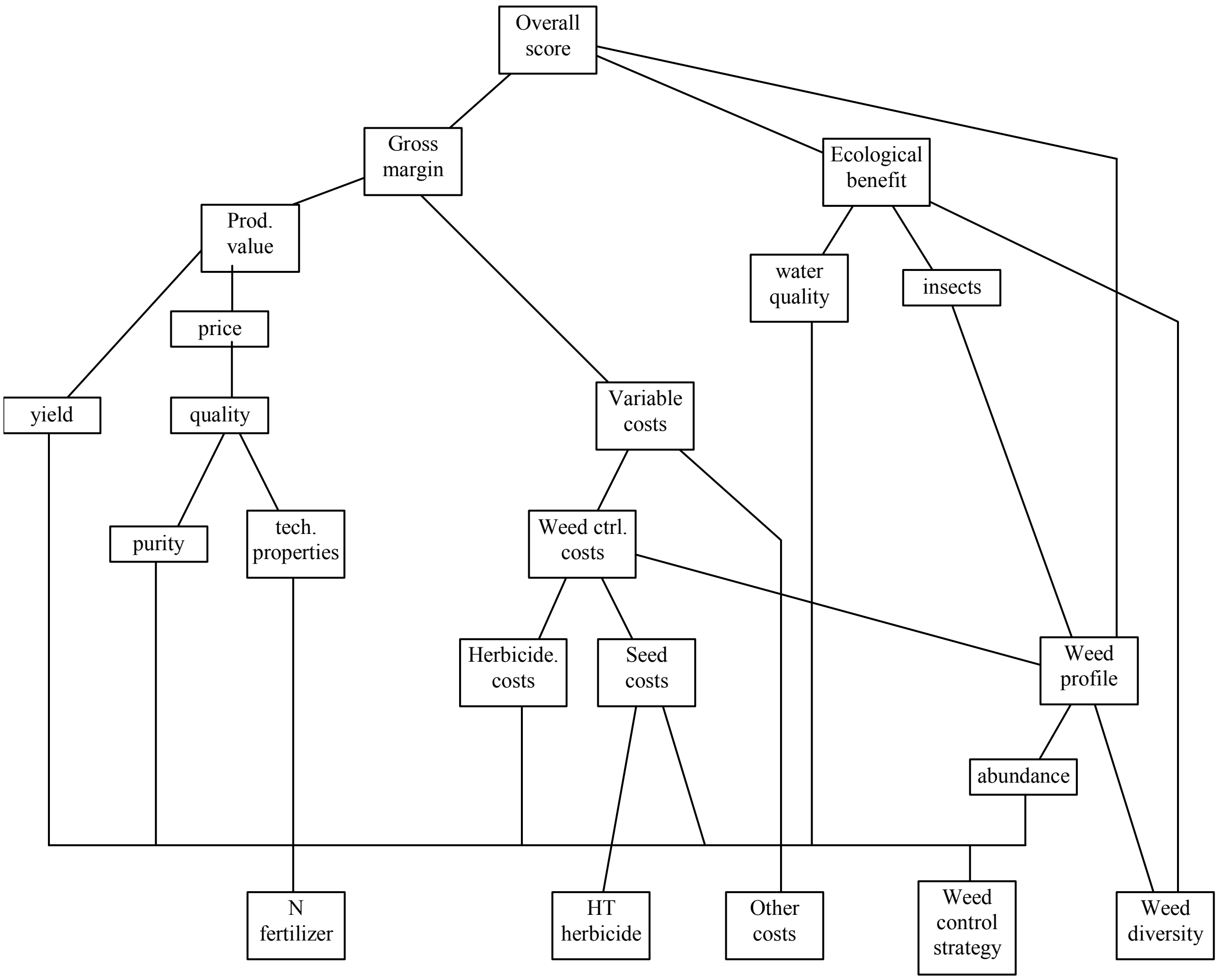

Figure 3: The hierarchical structure of the weed-control model.

Input attributes. The assessment of cropping systems is based on six input attributes:

1. *Weed_control_strategy*: the strategy of controlling weeds, either for conventional crops or for GM crops. The GM crops considered in this study are herbicide-tolerant (GMHT). There are six different strategies:
   a. Non-GM and simple pre-sowing herbicide application (pre_sowing trifluralin);
   b. GMHT with one fall application of herbicide;
   c. GMHT with fall + spring applications of herbicide;
   d. Non-GM with pre-sowing+pre-emergence applications of herbicide;
   e. Non-GM with pre-sowing+post-emergence applications of herbicide;
   f. Non-GM with post-emergence application of herbicide only.
2. *HT_herbicide*: the application of HT herbicide: glyphosate, none, glufosinate, or generic.
3. *N_fertilizer*: the application of nitrogen fertilizer: high (>200 kg/ha), medium (150–200 kg/ha), or low (<150 kg/ha).
4. *Weed_diversity*: the diversity of weed at the location studied: high, medium, or low.
5. *Other_costs*: relative estimation of marginal costs other than weed control costs: high, medium, or low.
6. *Fixed_costs*: relative estimation of the fixed cost of production: high, medium, or low.

Aggregate attributes. The aggregate (intermediate) attributes are grouped into three main subtrees:

1. *Weed profile* is an aggregate sub-model that affects several other parts of the model. Basically, it defines the weed profile according to the abundance and diversity of weeds.
2. *Gross margin* is estimated on the basis of Production value and Variable costs of production. Production value depends on yield and quality, which in turn depends on purity and technological properties of production. Variable costs are estimated on the basis of herbicide costs, seed costs and weed profile.
3. *Ecological benefit* is estimated according to water quality, insects and weed diversity. The effect on insects is assessed through weed profile.

All the aggregate attributes in the model are assessed according to rules defined by an expert. Figure 4 shows two such rulesets, conveniently presented in a tabular form. The bottom ruleset defines the mapping between the input attribute *Weed_control_strategy* to the aggregate attribute *Abundance*. The top ruleset defines the rules that combine *Abundance* and *Weed_diversity* into the aggregate attribute *Weed_profile*.

	Abundance	weed_diversity	Weed_Profile
	22%	78%	
1	***high***	<=medium	high_potential_problems
2	<=medium	***high***	high_potential_problems
3	medium	medium	regular_problems
4	low	***high***	regular_problems
5	low	>=medium	low-problematic
6	<=medium	low	specific_flora_problems

	weed_control_strategy	Abundance
	100%	
1	simple pre-sowing	***high***
2	HT one fall application	medium
3	>=pre-sowing+pre-emergence	medium
4	HT fall + spring applications	low

Figure 4: Two tables of aggregation rules: for Weed profile and Abundance of weed.

3.2 Pest-control model

In addition to the weed-control model, we have also developed a pest-control model. Its structure is similar to the weed-control model, with the following differences:

- The subtree *Weed control* is replaced by a subtree *Pest control*, having similar structure, but different attribute values and aggregation rules.
- Two new attributes are added to the node *Ecological benefit*: *Greenhouse gasses* and *Soil*. *Soil* is in turn composed of *Soil fauna* and *Soil quality*.
- The attribute *Purity* is replaced by *Damage*.

4 Economic assessment

Figure 5 shows the structure of the ECONOMY submodel for the assessment of economical indicators. This model assesses gross margins at the *level of a single farm* for *Bt-corn*. [Bt-corn has been genetically engineered to produce an insecticide known as Bt-toxin, produced by a naturally occuring soil organism Bacillus thuringiensis (Bt).] In addition to the ECONOMY submodel, some possible links for the ECOLOGY submodel are also shown in Figure 5.

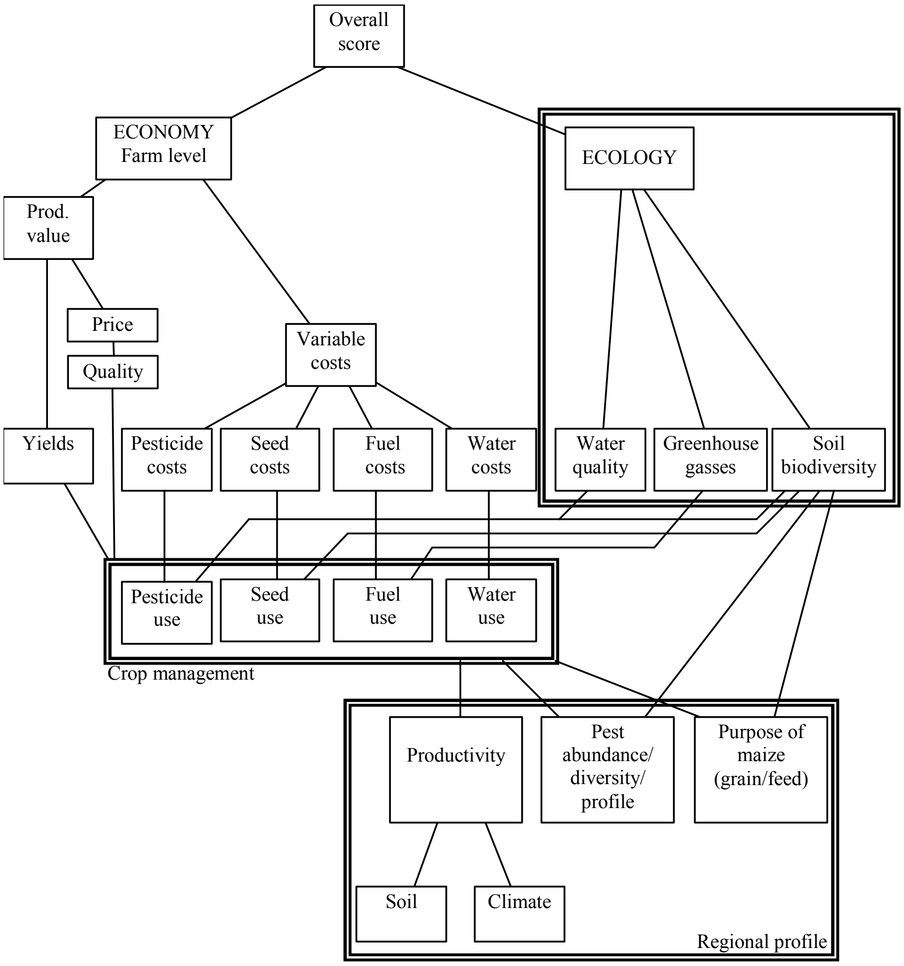

Figure 5: Hierarchical structure of the ECONOMY model (Bt-corn, farm level).

Basically, the farm level impacts in terms of economy depend on *Production value* and *Variable costs*. The former can be determined on the basis of *Price* and *Yields*, where *Price* depends on the *Quality* of production.

Variable costs incorporate the costs of *Pesticides*, *Seeds*, *Fuel*, and *Water*. Each of these costs directly depends on the *use* of the respective item: pesticides, seeds, fuel, and costs. The used quantities of each of these items, as well as *Yields* and *Quality*, directly depend on the cropping system employed at the farm level. Thus, these four variables form a group referred to as *Crop management*. Notice that some of these indicators affect the ECOLOGY part of the model, too. For instance, *Pesticide use* influences *Water quality* and *Soil biodiversity*. The latter is affected by *Seed use*, too. *Fuel use* influences *Greenhouse gasses*.

The lowest level of attributes form the group called *Regional profile*. These attributes describe the properties of a particular region in terms of: *Productivity*, *Pest abundance*, *Purpose of maize* (which can be used for grain or feed). *Productivity* depends on the characteristics of *Soil* and *Climate* in the region. Notice that all the three main attributes of *Regional characteristics* affect the *Crop management* group, and that two of them (*Pest abundance* and *Purpose*) additionally affect *Soil biodiversity*.

When we move from the farm level to the *regional level*, a new important factor comes into play: *Adoption rate*. Namely, when assessing a cropping system at the farm level, it is clear whether Bt-corn has been adopted in that system or not. It can only be adopted or not adopted, there are no intermediate choices. However, when assessing a cropping system at the regional level, it becomes important which proportion of the farms have adopted Bt-corn, because the adoption rate influences the *Regional yields* and *Regional costs* of the crop. Also, the adoption rate itself can be influenced by the *Price* in the market, which introduces a cycle into the model.

All this is reflected in the strucure of the ECONOMY model for Bt-corn at the regional level (Figure 6). The structure is very similar to the structure of the model at the farm level (Figure 5), except that there is an additional block appearing above the *Crop management* block. This new block assesses *Adoption rate* based on *Field trial yields* and *Field trial costs*. Both of these variables depend on the indicators of

Crop management, which in turn depend on the assessed cropping system. Once determined, *Adoption rate* directly influences *Regional yields* and *Regional costs*.

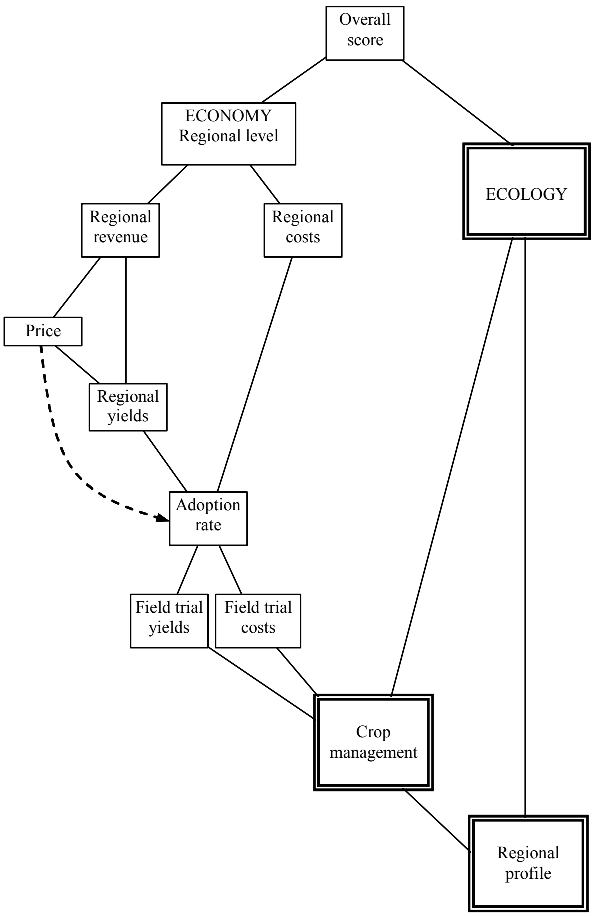

Figure 6: Hierarchical structure of the ECONOMY model (Bt-corn, regional level).

5 Conclusion

The modeling of economic and ecological impacts of genetically modified crops is inherently difficult. It requires knowledge from different fields and disciplines, which is scarce and largely unknown. It also requires complementary approaches, such as a combination of data mining and expert modeling, which has been attempted in ECOGEN. The benefits of modeling, however, are manifold, as it facilitates various computer-based assessments, evaluations, analyses and simulations. The results are eagerly awaited by European administration, politicians, ecologists, farmers and the interested public.

The models presented in this paper provide a preliminary step in this direction. They are in an early development stage and a lot of further work is expected. First, the models should be tested using real field data which is being collected. The models and their results should be evaluated by relevant experts. Second, the developed models are truly hierarchical (as opposed to traditional tree-like structure) and involve some very complex relationships between attributes, even cycles. These characteristics exceed the capabilities of currently available supporting software, which will have to be accordingly modified and extended. Last but not least, the developed models provide just a part of the final integral model, which will address additional cropping system control mechanisms and additional GM crops.

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