The integrated model network ITE^{2}M: model set-up and assessment of agricultural land use and management options

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Abstract: The Integrated Tool for Economic and Ecological Modelling (ITE^{2}M) is developed to assess landscape services of different land use options. ITE^{2}M is a network of several models addressing agro-economy, agricultural policy and environmental services with respect to soil, water as well as floral and faunal biodiversity. As a central part of ITE^{2}M the agro-economic simulation model ProLand predicts land use distributions that are optimal from an economic point of view. ProLand calculates the spatially differentiated maximum land rent accounting for different natural, technical, economic and political boundary conditions. The site specific outputs of ProLand comprise land rent, land use and in particular management information (e.g. crop rotation, fertilizer application, tillage). This data form the basis for other ITE^{2}M models. The eco-hydrological model SWAT investigates the effects of these land use options on the water balance and water related nutrient fluxes. The model ATOMIS is applied to estimate the fate of heavy metals in top soils considering respective thresholds for a sustainable soil management. This paper focuses on the interdisciplinary approach of ITE^{2}M. It emphasizes the interaction of the three aforementioned models with particular respect on the integration of ProLand land use and management data and SWAT hydrologic information to predict heavy metal accumulation in soil.

Keywords: environmental risk assessment; heavy metals; integrated modeling network; land management modeling; land use modeling

1 INTRODUCTION

Landscapes provide a wide range of services, comprising employment, economic income, habitat for fauna and flora, water supply, or food production amongst many others (Costanza et al., 1997). As landscape services are very much depending on the land use type and management system, changes in the land use and management might lead to changes in the landscape service in turn. The evaluation of changes in land use or management systems should be considered in view of several landscape services and their interactions concurrently. Integrated modeling approaches can be used to evaluate agricultural policy, which lead to different land use and management patterns in a landscape.

European Common Agricultural Policy (CAP) has changed radically over the years. The MacSharry reforms of 1992 and the AGENDA 2000 package attempted to reduce the price support for single crops, even though the largest shares of subsidies were still directed towards produced volume. In 2003 Europe Union (EU) farm ministers adopted a fundamental reform of the CAP with emphasis on direct payments to farmers, assumed as the best way of guaranteeing farmer incomes, food safety and quality as well as environmentally sustainable production.

Different indicators regarding economic, social and environmental terms can be used for an integrative assessment of landscape services. In terms of environmental pollution, the heavy metal status of soils appears to be a suitable indicator to evaluate sustainable land management. Agricultural heavy metal input into soils is mainly dependent on type (e.g. sewage sludge, animal manure, mineral fertilizer) and amount of fertilizer application (Nicholson et al., 2003), whereas the latter depends on crop rotation and potential yield. The fate of heavy metals, i.e. whether they are sorbed or leached out, depends on the soil sorption characteristics which are either stable like texture or labile like pH-value and soil organic carbon content (SOC). Labile soil properties are specially dependent on land use and management. Dissolved metals can be leached out or taken up by plants.

This study presents the model-setup of the Integrated Tool for Economic and Ecological Modeling (ITE^{2}M) with a focus on inter-model data exchange. The conceptual description of the approach is followed by an exemplary application of ITE^{2}M. Agricultural land use and management options are assessed in terms of potential heavy metal accumulation in top soils under the light of the Common Agricultural Policy of the EU.

2 MODEL NETWORK ITE^{2}M

The integrated model network ITE^{2}M was developed at the Collaborative Research Center (SFB 299) for the sustainability assessment of land use options. ITE^{2}M comprises several models addressing agro-economy (ProLand), agricultural policy (CHOICE) and environmental services with respect to risk of soil pollution (ATOMIS), water quantity and quality (SWAT) as well as faunal (GEPARD) and floral (ProF) biodiversity (Fig. 1).

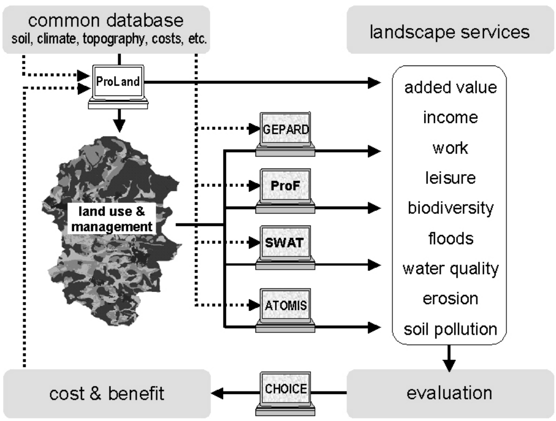

Figure 1. ITE^{2}M-model-network setup

As the central part the agro-economic model ProLand predicts site specific land use. These maps and further model specific information form the basis for all ITE^{2}M members to simulate economic and ecological landscape services. Trade-offs and win-win situations (e.g. Frede et al., 2002) between these landscape services are calculated and can finally be evaluated within ITE^{2}M.

This paper focuses on the interaction of the three models ProLand, SWAT, and ATOMIS. Hence, an overview of these three models is given in the following.

2.1 ProLand

The bio-economic simulation model ProLand is a comparative static model predicting the spatially explicit allocation of land use systems (Kuhlmann et al., 2002; Möller et al., 2002). The basic assumption for the model is that land users select the land use alternative from a set of agricultural and silvicultural land use systems which may be expected to generate the highest possible lend rent on a decision unit (Kuhlmann et al., 2002; Weinmann et al., 2006). Land rent in this context is defined as the sum of monetary yields including all subsidies minus input costs, depreciation, taxes, and opportunity costs.

Calculating the land rent takes several steps (Weinmann, 2002). First ProLand estimates the site-specific maximum realizable yield. Therefore specific data such as soil type, accumulated temperature, and long-term mean annual precipitation in growing season are used as inputs to determine this yield. The second step is the calculation of the production costs adjusted for natural and site conditions such as slope, field size and soil tillage resistance. The land rent maximization is carried out for every decision units. For each unit the economically best land use system is found. A land use systems however is a predefined production process including all sub-processes in crop and animal production like e.g. seedbed preparation, plant protection or milking.

ProLand can be applied in a grid and vector mode. In this example ProLand is used in the grid mode with a 25 m grid resolution being the decision units in this study. The output of ProLand includes a set of economic key indicators as well as maps of land use with site specific management information (e.g. crop rotation or fertilizer application).

2.2 SWAT

The Soil Water Assessment Tool (SWAT, Arnold et al., 1998) is a semi-distributed eco-hydrological model that combines conceptual and process orientated approaches. It is used for runoff-prediction and calculation of river N- and P-concentration within the ITE^{2}M framework. Based on a digital elevation model, the catchment is partitioned into a number of subbasins, which have a spatial explicit location. Water is routed between the subbasins with a kinematic wave approach. A further subdivision of the subbasins into Hydrological Response Units (HRU) is based on land use and soil information. A HRU does not have a spatial explicit location within a subbasin, i.e. it is a lumped land area comprised of a unique combination of land use and soil type. Thresholds of 7 and 5 % are used in the present work to define the minimum area of soil and land use to be represented in each HRU. For the calculation of hydrological fluxes we used SWAT-G, a model version adapted for the application in low mountainous catchments with its typical shallow rock aquifers and a high portion of interflow (Eckhardt et al., 2002). In SWAT-G, an anisotropy factor, which is defined as the ratio between horizontal and vertical saturated conductivity, is used to simulate increased lateral flow typical for low mountainous catchments in Germany. In addition, a soil horizon with a high bulk density and a low available water content is added below the regular soil profile to account for the geo-hydrological characteristics of the fissured rock aquifers in these catchments. Prior to model application, SWAT-G has been automatically calibrated and successfully validated (Eckhardt and Arnold, 2001, Huisman et al., 2003). In this study, SWAT model simulations are conducted for the period of 01.01.1980 to 31.12.2002, whereby the first two years act as a warming up period.

2.3 ATOMIS

The Assessment Tool for Metals in Soils (ATOMIS; Reiher et al., 2004) prognoses site-specifically long term development of heavy metal concentration in top soils. ATOMIS is parameterized for Ni, Cu, Zn, Cd, and Pb. These potential toxic elements are of concern due to existing legally threshold values in many countries (e.g. BBodSchV, 1999). Metal input by land management is derived from ProLand P-fertilizing data. Metal input by atmospheric deposition is according to data of a gaging station, which uses the “Bergerhoff”-method and which is representative for peripheral regions in Hesse.

Pedotransfer functions estimate the element concentration in soil solution which can be removed from the top soil by leaching and plant uptake. They are parameterized by soil sorption characteristics such as pH-value, SOC, clay content, and heavy metal content of the soil. The metal concentration in soil solution is calculated using general purpose Freundlich isotherms according to van der Zee and van Riemsdijk (1987) and Horn (2004) from EDTA-extractable metal content. This fraction is calculated from total metal content by regression functions, which are derived from laboratory data. LABO (2003) provides so called heavy metal background values which enable an allocation of total metal concentrations in top soils due to different geologic units. ATOMIS can identify areas, where geologic background combined with site characteristics like soil properties and seepage water lead to potentially problematic enrichment of heavy metals due to agricultural land use and management. Sustainability of land use and management options can be assessed by comparing the predicted future total metal concentrations in top soils to legally specified threshold values after a defined period of time.

3 INTER-MODEL DATA EXCHANGE

One of the key aspects of ITE^{2}M is the inter-model data exchange. Apart from the fact that ProLand provides land use maps to the other models, there is additional data exchange and back-coupling between the models.

3.1 ProLand-SWAT

SWAT has a stand alone crop growth simulation module that requires detailed management information on nutrient supply. ProLand provides this information by estimating site explicit N and P demands. The demands are used to estimate average N and P fertilization rates for the SWAT simulations. The most prevailing crop rotation and pasture system as predicted by ProLand are assumed to cover the entire agricultural and pasture land, respectively.

3.2 SWAT-ATOMIS

ATOMIS requires geographically explicit information on seepage water and transpiration rates. Seepage water is needed to calculate the amount of heavy metals leached from top soil, while transpiration rate is used to quantify metal uptake by plants. We used SWAT estimates on mean annual percolation rates from the top soil horizon and mean annual evapotranspiration rate as input for ATOMIS.

Since SWAT is a semi-distributed hydrologic model, results for the smallest scale refer to HRUs.

The relocation of HRUs is done following the approach developed by Haverkamp (2005). Here HRUs are redistributed to a grid map for the entire catchment by their spatially known aggregation information of soil type, land use and subbasin affiliation. Evapotranspiration data is multiplied according to Wohlrab et al. (1992) by the factor of 0.55 (arable land) and 0.60 (grassland and forest) to estimate the transpiration rate.

Detailed knowledge on site-specific hydrological data is of importance for estimating element outputs of soils by leaching and plant uptake when calculating heavy metal balances. The usage of SWAT results in ATOMIS proved to be a useful application beyond its initially intention. The main advantage is the use of the same land use data and scale for different scenarios. External data on seepage and evapotranspiration rate have a rather coarse scale and they are derived using a present land cover classification. Thus land use and management reflected differences between scenarios would be ignored. Since different land use scenarios are assessed by all ITE^{2}M-models SWAT provides different distributed hydrologic data due to these scenarios.

3.3 ProLand-ATOMIS

Labile soil sorption characteristics are influenced by land use and management. As ProLand assumes site-specifically adjusted land management production systems, ATOMIS assigns generally accepted land use and soil texture depending pH-target-values (Fürchtenicht et al., 1993) to each site. Additionally, three classes of SOC are implied separating agricultural land from forest and arable land from grassland.

Phosphorus demand is calculated from algorithms estimating the maximum realizable yield for each decision unit by ProLand. In ATOMIS the type of added P-fertilizer is allocated to each site depending on the site specific production system. Cattle manure is only applied to sites of cattle forage production. These production sites are grassland as well as arable land with crop rotations that include the production of cattle fodder as silage maize and clover-grass. As there is a P-export out of the agricultural system via milk and meat it is assumed by ATOMIS that the site-related difference between P-removal and P-input by cattle manure is substituted by mineral P-fertilizer. All sites without cattle forage production are completely fertilized by P-fertilizer.

The advantage of using site explicit land use models such as ProLand is, that spatially explicit data on P-fertilizer demand are available that are a prerequisite for any regional heavy metal modeling approach. Furthermore, from land use and crop rotation data the quality of a fertilizer applied to a site with respect to heavy metal concentration can be estimated. Thus it is ensured, that the total amount e.g. of cattle manure in a region is approximately calculated. Problematic areas due to heavy metal concentration in soils can be assessed. Nevertheless, the site-specific ProLand approach bears the problem, that as ProLand has no knowledge on location of any farms, the assumed distribution of farmyard manure is not on all sites the distribution which would reveal under currently existing conditions. However, because ProLand and ATOMIS assume no over-fertilization, this model limitation is appreciated to be the only possible way of sustainability assessment as all other distributions of fertilizer would be arbitrary.

Finally, back-coupling ATOMIS results to ProLand can be used to calculate opportunity costs in terms of sustainable heavy metal criteria in soils as demonstrated by Reiher et al. (2005) in detail. This way of data exchange demonstrates the ITE2M potential for evaluating legally defined threshold values and enables their economic assessment.

4 EXEMPLARY RESULTS OF ITE^{2}M

In order to show the various economic and ecological feedback mechanism of ITE^{2}M we assessed the heavy metal status of agricultural top soils for two land use scenarios: the AGENDA 2000 reflects former EU agricultural policy whereas CAP addresses the agreements of the 2003 CAP reform (see Weinmann et al. (2006) for detailed scenario description). The land use scenarios were developed for the mesoscale, low mountainous Dill river catchment in Hesse, Germany (ca. 693 km^2). The spatial resolution was 25 x 25 m.

The land use distribution is 9.6 % (6687 ha) for arable land, 6.5 % (4526 ha) for grassland, and 73.9 % for forest in the AGENDA 2000 scenario and 0.5 % (344 ha), 29.9 % (20716 ha), and 58.0 % under CAP conditions, respectively.

The prevailing crop rotation simulated by ProLand for both scenarios is maize silage / maize silage / winter wheat. Grassland is simulated to be used extensively. Where animal husbandry is profitable, indoor stock keeping of cattle during the entire year, preprocessed by a plant production system producing cattle forage, is calculated by ProLand to be most effective economically. This is an important information as it is assumed that, if cattle are not grazing on meadows, they are fed with mineral dietary supplements, which are enriched with Cu and Zn. The total amount of cattle was calculated to 8965 animals in the AGENDA 2000 and 20566 animals in the CAP scenario.

Regarding the HRUs, 71.1 % of the Dill-catchment area could be directly redistributed for AGENDA 2000-scenario and 70.6 % for CAP-scenario. Fig. 2 gives an example for the hydrologic information provided by SWAT.

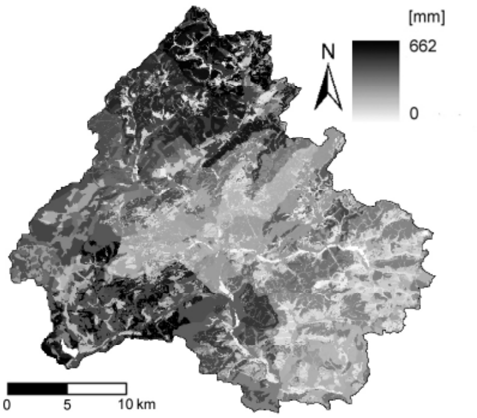

Figure 2. Redistributed hydrological information provided by SWAT: Seepage water beneath the top soil, CAP-scenario.

Fig. 3 shows an exemplary summary of the Cu fate in top soils of the Dill-catchment: Simulated concentrations were compared to precautionary values of the German soil protection ordinance (BBodSchV, 1999). Percentage of exceedance of the precautionary values is plotted against time.

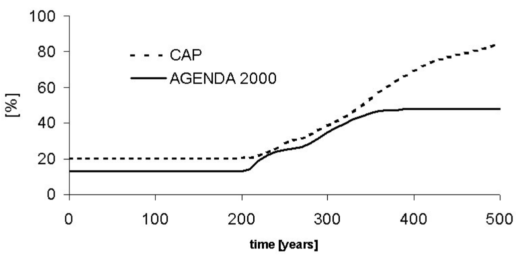

Figure 3. Percentage of agricultural land showing exceedance of precautionary value of Copper over 500 years.

13 % (1458 ha) of agricultural land in the AGENDA 2000-scenario and 20 % (4255 ha) in the CAP-scenario exceed precautionary value of Cu at the beginning of simulation, which is according to high geogenic background concentration in some areas. The percentages increase to 49 % (AGENDA 2000) and 85 % (CAP) after 500 years of simulated constant land use and land management.

5 DISCUSSION

Coupling site-specific management data, that determine agricultural heavy metal input to sites additionally to land use data allows an estimation of heavy metal accumulation in top soils and a risk assessment of land use and management options. Pig production is not relevant in the SFB 299 test region 'Dill river catchment', therefore it is not part of the fertilizer management. Hence, at present state ATOMIS predicts only effects of cattle manure and P-fertilizer when connected to ProLand. When transferred to different structured agro-regions, pork, egg, and poultry production systems will be adopted by ProLand and included within the ITE^2M-approach.

As SWAT is a semi-distributed hydrological model, the HRU-concept implies conceptual simplifications. Nevertheless, compared to other available digital data on seepage water (e.g. Duijnisveld et al., 2003) and evapotranspiration the advantages of using SWAT in this study were, that the same site characteristics, common spatial resolution, and detailed land use and management data were used across all models. Despite the limited spatial accuracy of the SWAT model, we think that the approach is sufficient for scenario comparison presented here. Therefore we consider any site specific hydrological information generated within the model network to be more process-orientated than using maps created from different input information and resolution. However, the approach of integrating hydrological information could be improved using a fully distributed hydrological model.

6 CONCLUSION

The developed methodology shows that site explicit modeling of land use and management provides a detailed basis for subsequent models to address environmental landscape services. Especially for scenario modeling, inter model data exchange based on a common site specific database can be useful. Taking management options into account the development of sustainable land use systems will be enhanced. Therefore there is a strong need for more model approaches regarding bidirectional data exchanges, that enable back-coupling of model results.

7 ACKNOWLEDGEMENT

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