INTERFACING GIS WITH A PROCESS BASED AGRO-ECOSYSTEM MODEL – CASE STUDY NORTH CHINA PLAIN

Georg Bareth[a,*], Zhenrong Yu[b]

[a] University of Cologne, Cologne, Germany, [b] China Agricultural University, Beijing, China

ABSTRACT:

The Sino-German Project between the China Agricultural University and the University of Hohenheim, Germany, focused on sustainable Agriculture in the North China Plain. One major focus of the project was the establishment of an experiment field near Beijing to investigate different agricultural practices and their impact on yield and environment. The second task was to set-up a GIS based Agricultural Environmental Information System (AEIS) for the North China Plain (NCP), which exceeds almost the size of Germany. Researchers from several departments are involved in the project: Agricultural Economics, Agricultural Informatics, Vegetable Science, Landscape Ecology, Phytomedicine, Plant Nutrition, Plant Production and Soil Science. The major aim of the AEIS for the NCP is to provide information (i) about agriculture in the region, (ii) about the impact of agricultural practices on the environment and (iii) of simulation scenarios for sustainable strategies. Consequently, the AEIS for the NCP provides information for decision support and therefore could be regarded as a Decision Support System (DSS), too. In this contribution, the focus is on the importance of the linkage of process-based agro-ecosystem models, here the DNDC model with GIS. The purpose of the linkage is the modeling of agro-environmental impacts on a regional level. Due to the geographic extent of the North China Plain, it could be regarded as national level as well. A key issue in the GIS-based regional modeling is the establishment of an adequate geodatabase which here is defined as a Agricultural Environmental Information System (AEIS). By using the database of the AEIS, it is possible in this case study to model with a process-based model the emission of N_2O, the volatilization of NH_3, and the leaching of NO_3^- from winter wheat/summer maize area for the entire North China Plain. Finally, the comparison with and evaluation of available models and methods (IPCC; SLUSA) for regional calculation is presented.

1. INTRODUCTION

The Sino-German Project between the China Agricultural University and the University of Hohenheim, Germany started in November 1998 for 4½ years and was located in Beijing. The focus of the project was on sustainable agriculture in the North China Plain (NCP) (http://www.uni-hohenheim.de/chinaproject). Sustainable agriculture is a big issue in China. One major focus of the project was the establishment of an experiment field near Beijing to investigate different agricultural practices and their impact on yield and environment. Investigated crops and vegetables were winter wheat, summer maize, spinach and cauliflower. For the crops, three factors were considered in the different treatments. There were three irrigation treatments (sub-optimal, conventional, optimal), three N-fertilizer treatments (sub-optimal, conventional, optimal), and two treatments of crop residues (with and without residues). For the vegetables, two irrigation treatments (conventional, optimal) and two N-fertilizer treatments (conventional, optimal) were considered. Intensive measurement equipment was installed on the experiment field to collect long term data of soil water, volatilization, and greenhouse gases. Plant and root data were sampled as well to provide all necessary data for intensive modeling evaluation and calibration. Additional investigations about pesticide, herbicide and fungicide applications have been carried out on the experiment field and in the outer Beijing area. Questionnaires were used to collect information about agricultural practices and the economical situation of the farmers. Finally, plant and animal monitoring and mapping were done to investigate the biodiversity in the study region.

Apart from the field experiment, the second task was to set-up an Agricultural Environmental Information System (AEIS) for the NCP (Bareth and Yu 2002), which exceeds almost the size of Germany. In the sense of Bill (1999), an Environmental Information System (EIS) is an extended GIS for the description of the state of the environment referring to critical impacts and loads. An EIS serves for the capture, storage, analysis and presentation of spatial, temporal and attribute data and provides basics for measures for environmental protection. The establishment of an AEIS for the simulation of sustainable scenarios means the set up of an extensive geo and attribute database. Especially the modeling of the C- and N-cycles in agro-ecosystems requires numerous input parameters like pH, soil texture, fertilizer N-Input, animal waste input, use of irrigation water, dates of sowing and harvest, yield, etc.. According to Bareth and Yu (2002), Fig.2 describes the elements of an AEIS. Due to the definition of an EIS and the defined aims of the AEIS for the NCP, an AEIS for sustainable agriculture includes five different information systems which are:

- Base Geo Data Information System (BGDIS)
- Soil Information System (SIS)
- Climate Information System (CIS)
- Land Use Information System (LUIS)
- Agricultural Management Information System (AMIS)

Most important for the spatial matching of all data in the AEIS is the integration of an BGDIS. The BGDIS should provide topographical data, elevation lines or a Digital Elevation Model (DEM) and an administrative boundary data set. The SIS is essential for providing soil parameters for the agro-ecosystem modeling. Therefore, the SIS has to include (i) spatial soil information in form of maps and (ii) a detailed description of the soil types including soil genesis, physical and chemical soil properties. The CIS provides the necessary climate/weather information. Climate/weather maps can be generated from point data using GIS interpolation methods. Land use data should be provided by a LUIS. Detailed land use information on crops should be stored in the LUIS. For detailed agro-ecosystem modeling, the information level in available land use maps is rather poor. The analysis of multi-spectral, hyperspectral and/or radar data from satellite or airborne sensor is a standard method to retrieve such kind of information. Finally, the AMIS is a crucial part. For the agro-ecosystem modelling, farm management data like fertilizer N-Input, animal waste input, use of irrigation water, dates of sowing and harvest, yield, etc. are a must. The AEIS is the sum of the described information systems. They are linked to each other using GIS technologies. Additionally, models and methods for data analysis have to be integrated in the AEIS. It is possible to link or even integrate complex agro-ecosystem models into GIS (Hartkamp et al., 1999) and consequently into the AEIS. Consequently, the AEIS for the NCP provides information for decision support and therefore could be regarded as a Decision Support System (DSS), too. The major objectives of the AEIS for the NCP are to provide information (i) about agriculture in the region, (ii) about the impact of agricultural practices on the environment and (iii) of simulation scenarios for sustainable strategies.

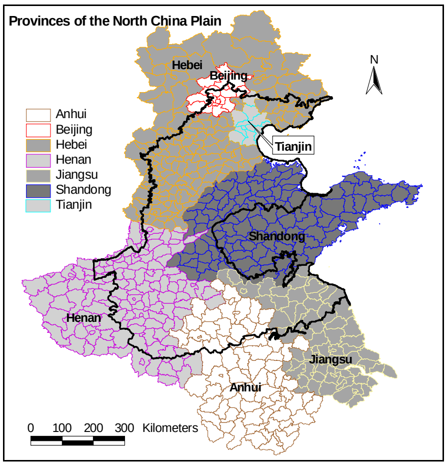

Figure 1. Provinces and geographical boundary of the NCP

2. INTEGRATION OF AGRO-ECOSYSTEM MODELS INTO GIS

Traditionally, process based agro-ecosystem models or agronomic models in general are developed and used for site or field scale. A major problem for regional applications of such kinds of models is the limited regional data availability. The scientific and technical progress in spatial sciences, especially in GIS and remote sensing (RS) technologies, have enabled the set up of soil, land use, climate and agricultural management information systems. Unfortunately, complete data sets for regions are hardly available and therefore the regional application of agro-ecosystem models is still difficult. Lack of data availability can nowadays solved by using again GIS and RS technologies. Therefore, interfacing GIS with agro-ecosystem models is becoming more important.

Seppelt (2003) describes the coupling of GÌS and models in a theoretical and technical context. Hartkamp et al. (1999) introduce four different ways to interface GIS with agronomic models. They also introduce definitions for the different ways of interfacing. This is an essential point because the use of not defined terminology causes confusion. Hartkamp et al. (1999) define four terms which are frequently used as follows:

- Interface: The place at which diverse (independent) systems meet and act on or communicate with each other.
- Link: To connect.
- Combine: To unite, to merge.
- Integrate: To unite, to combine, or incorporate into a larger unit; to end segregation.

The three different methods of interfacing GIS with models are described as followed. *Linking* of GIS with models is basically just an exchange of files or data. In this case, the model is independent from the GIS and vice versa. Only the results of each system are exchanged. *Combining* of GIS with models involves processing of data and automatically exchange of data. Finally, *integrating* GIS and models describes the real incorporation of one system into the other.

Hartkamp et al. (1999) give a very good overview of examples of interfacing GIS and models. They describe 46 publications. While the interface type of 22 of the GIS-model interfaces is linking, 23 represent combining and only 6 are of the integrating type. None of the described integrating GIS-model interfaces are for agro-ecosystem models focusing on C- and N- dynamics. Most of them deal with topography, soil erosion and groundwater flow.

Especially for the regional modeling of C-and N-dynamics in (agro-)ecosystems on a regional scale, the integration of such models is important and can be regarded as a key issue. Available approaches of GIS-model interfaces for agro-ecosystem models hardly use the GIS analysis capabilities. For example, the Denitrification and Decomposition Model (DNDC) (Li et al., 2001) has, in its latest versions, a regional model part included. Spatial parameters like land use and soil are not considered in their spatial relation. GIS is just used for result display on county level using a county map. Plant (1998) describes a GIS-DNDC-interface of the linking type for the Atlantic zone of Costa Rica. This study shows clearly the importance of interfacing agro-ecosystem models with GIS. This introduced approach is not automated and consequently very difficult to use for other regions. Therefore, we introduce a method for integrating agro-ecosystem models into GIS which enables fully automated spatial model simulations.

In this approach, we use the DNDC model for the integration into a GIS. The DNDC Model was developed at the University of New Hampshire in the early 90s (Li, 2000). Its original purpose was the simulation of N_2O and NO gas fluxes from agricultural fields on a daily basis, but it also has a very detailed soil C sub-model. It is currently the most used simulation tool for N related gas fluxes and has been used for county based national inventories of N_2O for China (Li et al., 2001), the USA (Li et al., 1996), the UK (Brown et al., 2002), Germany (Werner 2003) and several more countries. The soil organic matter sub-model is made up of three different soil C pools with each being divided into a labile and resistant fraction. The plant growth sub-model rather simply models biomass at a potential growth rate which is modified by environmental factors. The driving key variables are climate, soil properties, and agricultural management. Even though it has a very simple plant growth sub-model it is capable of simulating trends in soil C quite accurately (Li et al., 1997). In another simulation study of an arid farmland ecosystem in China the DNDC model was also able to model the influence of different management practices on soil C content (Liang and Xu, 2000).

3. SLUSA-BASED INTERFACING OF GIS WITH MODELS

The method for the integration of agro-ecosystem models is based on the soil-land-use-system approach (SLUSA) (Bareth et al., 2001). The SLUSA is based on the ecosystem approach described by Matson and Vitousek (1990). This ecosystem approach was furthermore disaggregated in order to estimate and visualize the greenhouse gas emissions (CH_4, CO_2, N_2O) from agricultural soils for a distinct region (Bareth 2000). The disaggregation of the ecosystem approach was undertaken by using a GIS and available digital spatial data (Bareth 2000). The SLUSA is a GIS and knowledge based approach for environmental modeling. The first step of the SLUSA is the set up of a GIS which contains relevant data. In the second step, GIS tools are used to overlay climate, soil, land use, topography, farm management, and other data like preserved areas or biotope (if available). This procedure is the basis for the spatial related identification of different soil-land-use-systems. In the third step, emission data and process knowledge of the region of interest as well as from literature are linked to these systems. For the linkage, N_2O emissions potential classes are created and knowledge based production rules are programmed. The latter ones are commonly used to generate new knowledge from expertise in knowledge based systems like expert systems (Wright et al., 1993). Available data from the region of interest are considered with higher priority. Finally, GIS software tools are used in the fourth step to visualize and to quantify the generated emission data. The quantitative emission estimation is done by multiplying the areas of each N_2O emission potential class with the representative value of each class. The new spatial emission data can be integrated into other regional models like regional farm models (Bareth and Angenendt, 2003).

Based on the SLUSA, Fig.2 describes the integration of agro-ecosystem models into GIS. While the steps 1, 2 and 4 remain in the method, the third step of the SLUSA is changed. The implementation of the knowledge based production rules of the SLUSA is replaced by the integration of the agro-ecosystem model. All input parameters for the model derive from the GIS database. The advantage of this method is the automatic spatial modeling. The GIS integrated DNDC model uses the input parameters from the fields of the GIS database. Therefore, the DNDC model program code was changed for that purpose and necessary interfaces were programmed (Huber et al., 2002). For the input, fixed field names were created in the DNDC model and the GIS database must use these definitions. The results of the model runs are automatically written into predefined fields of the GIS database. Consequently, the results of the modeling can immediately be used for regional calculation and visualization by using GIS software tools. Finally, a new menu button is integrated in ArcGIS which allows the user the easy to use access for DNDC modeling.

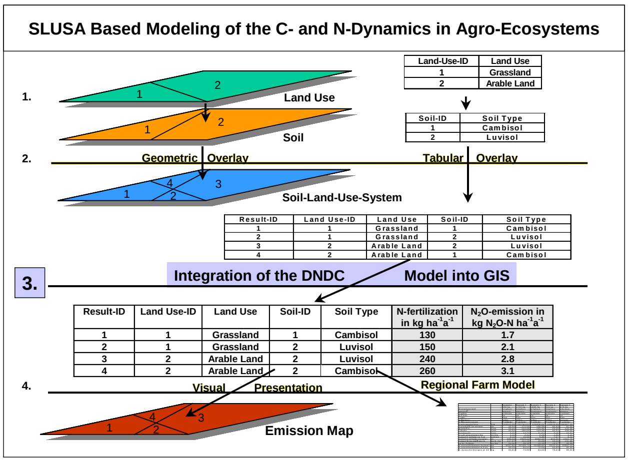

Figure 2. SLUSA based integration of process orientated agro-ecosystem models into GIS

Evaluation of models is a very important step. For this procedure, measurement data is necessary. For Dongbeiwang Township, the evaluation of the DNDC model can be done by using measurement data from the experiment field. For example, measurements of gas fluxes with the automatic closed-chambers-technique are available from the research project. The chambers and the automatic measurement system are mainly designed by Martin Kogge of sub-project B2 of the Sino-German Project (http://www.uni-hohenheim.de/chinaproject/martin.htm). The chambers are designed to measure CO_2, CH_4 and N_2O. For the three different treatments, measurements are done with three repetitions per plot. The treatments are conventional fertilization and irrigation, optimized fertilization and irrigation, and conventional fertilization and optimized irrigation. N_2O measurements are available for summer maize 2001. For the traditional treatments, the total emission for the period of 06-21-01 to 10-09-01 for summer maize is 2.35 (± 0.48) kg N_2O-N ha^{-1}.

4. RESULTS

In Fig.3, the data of the AEIS for the North China Plain is displayed. The official digital topographic database (1:250,000) was purchased as Base Geodata Informationsystem (BGDIS). On national level, the Institute of Geomatics in Beijing is responsible for topographical data. In 1999, they finished the digital topographical database on the scale 1:250,000 (DTD250) in vector format. They provide the data as ArcInfo coverages and many other GIS formats. The data set includes separate files for rivers, lakes, roads, railways, cities, one degree net, 50 m contour lines and administrative boundaries (counties, districts, provinces) (Bareth and Yu, 2004). The layers were digitized from the topographical maps on the same scale. The dates of the maps range from the early to the late eighties. A DEM, generated from the contour lines, is available, too.

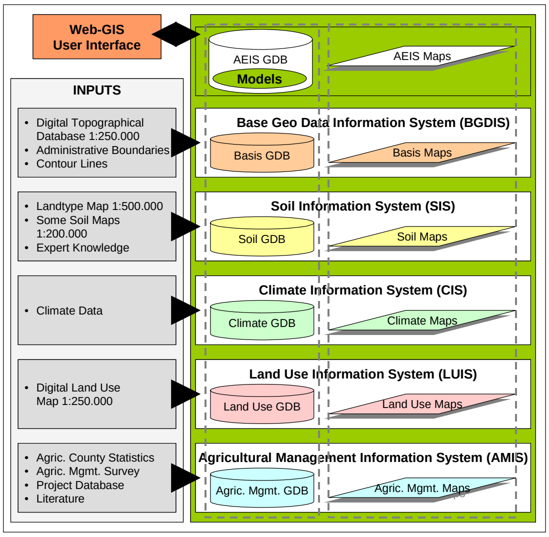

Figure 3. AEIS for the North China Plain

Compared to the availability and the access of topographical and land use data, soil data are much more difficult to get in China. Several soil maps in a scale of 1:200,000 were digitized. The problem here was the lack of information about the soil properties. Therefore, the landtype map 1:500,000 for the North China Plain was digitized and soil properties for the soil units derive from a Chinese soil text book.

The Climate Information System (CIS) consists of daily weather data for the years 1999-2002. The weather data was purchased via the German Weather Service (DWD) for 9 weather stations in the North China Plain. Thiessen polygons were then created to provide spatial weather data on a daily base. Similar approaches were used by Mathews and Knox (1999).

Digital spatial land use data are available in China on the scales 1:250,000 and 1:100,000 in ArcInfo vector format. The land use data derive from LandsatTM land use classifications. The Institute of Remote Sensing Applications (IRSA) of the China Academy of Sciences in Beijing is responsible for the land use classifications. For the North China Plain, the data was obtained in 1:250,000. Additionally, statistical county data for the same years were obtained.

Finally, the Agricultural Management Information System (AMIS) was created on the base of statistical county data, available survey data, data of the research project and from literature. For each weather region, a specific management for the wheat/maize rotation is specified.

All the mentioned data are organized in the frame of the AEIS which is GIS-based. Consequently, it is possible to identify unique weather-soil-land-use-management systems (agro-ecotopes). Approximately 240,000 polygons were created overlaying the spatial soil, land use and weather data. By using database functionalities within the GIS 285 unique agro-ecotopes for the considered wheat/maize rotation are identified. The parameters of these 285 agro-ecotopes are used as input for the DNDC model in the site mode. The final result of this modeling process for the North China Plain is listed in Tab.1. The spatial distribution of e.g. the emission of N_2O is presented in Fig.4.

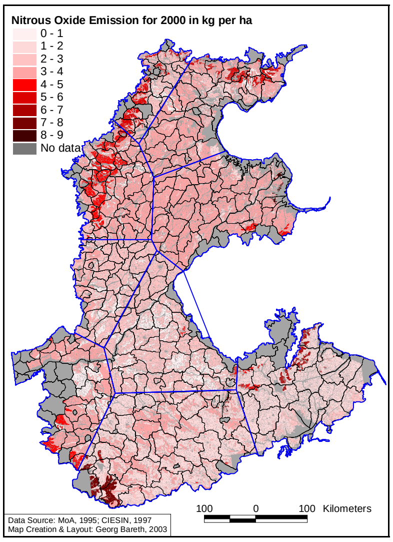

Figure 4. N_2O emission from summer maize/winter wheat areas in the North China Plain

Table 1. Annual N2O-emission, NH3-volatilization and NO3-- leaching for the summer maize/winter wheat area of the North China Plain (DNDC model)

Year	N_2O	NH_3	NO_3^-	Total
	Gg N yr^{-1}			
1995	52	1358	426	1837
2000	53	1373	429	1855

5. DISCUSSION AND CONCLUSIONS

Li et al. (2001) model a national inventory of N_2O emissions from arable lands for the whole of China with the process-based DNDC model. The input parameters for the model are daily minimum and maximum air temperature, daily precipitation, nitrogen deposition, soil texture, pH, organic matter content, individual crop areas, N-fertilizer use, livestock and human populations, tillage management, irrigation management, planting and harvest dates, and crop residue management. Most of the agricultural parameters derive from official census data. The authors model low N_2O emissions for the North China Plain. This does not correspond to the daily field measurements of summer maize in 2001 which are presented in this contribution. One explanation could be that the measurements of 2001 cannot be compared to the model results of data of 1990. But from process knowledge, high emissions from summer maize are expected due to high precipitation, high temperatures and high N-input during the growing season. Another explanation for the low regional model results could be that the used data of the agricultural census which do not reflect the agricultural practices of distinct crop management. Only average N-fertilizer data per county are available. Additionally, the quality of the census data has to be discussed in general. Tso et al. (1998) mention that the census data are not reliable and there are wide discrepancies e.g. of about 25 – 40 % of just how much agricultural land are actually under cultivation. The question therefore is if regional modeling of agro-ecosystems should be based on knowledge based agricultural practices for the different crop managements. This would make detailed agricultural land use maps an essential tool for regional agro-ecosystem modeling. Consequently, RS would become a key tool to provide the basics to generate the input parameters for regional agro-ecosystem modeling. Finally, using census data as input parameters for regional modeling the impact of this data source should carefully be discussed.

Table 2. Annual N2O-emission, NH3-volatilization and NO3--leaching for the summer maize/winter wheat area of the North China Plain (IPCC)

Year	N_2O	NH_3	NO_3^-	Total
	Gg N yr^{-1}			
1995	61	433	1300	1794
2000	62	438	1313	1813

Table 3. Annual N_2O-emission, NH_3-volatilization and NO_3^--leaching for the summer maize/winter wheat area of the North China Plain (SLUSA)

Year	N_2O	NH_3	NO_3^-	Total
	Gg N yr^{-1}			
1995	27	975	960	1962
2000	27	985	970	1982

Additional results of regional modeling of annual N_2O-emission, NH_3-volatilization und NO_3^--leaching are presented in Tab.2 and Tab.3. Different modeling approaches were used. In Tab.2 the results of the empirical method for national greenhouse gas inventories of the International Panel on Climate Change (IPCC) are presented. This empirical method bases of the application of given factors usually multiplied by numbers deriving from county statistics. While the total amount of N losses are very similar to the modeling results of the DNDC (Tab.1), the numbers for NH_3- and NO_3^--losses are almost vice versus.

In Tab.3 the results of the GIS- and knowledge-based approach (SLUSA) are listed. The overall N-losses are again in the same range of the previous discussed results. But the losses from N_2O-emission, NH_3-volatilization and NO_3^--leaching vary significantly from the results of the DNDC model and the IPCC method. Very interesting is the small amount of simulated N_2O-fluxes. Overall, the results of the SLUSA are considered to be most realistic because regional measurements are integrated in this approach. Therefore, evaluation and calibration of the DNDC model and the IPCC method has to be done on a regional level.

In this contribution, it is clearly shown that the potential of linking GIS and agro-ecosystem models is huge. Key problems in this regional modeling approach are still data availability and evaluation and calibration of the agro-ecosystem models. Regional AEIS has to be established for general regional modeling and more regional measurement data has to be available for these purposes as well as for the assessment of the simulation results.

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