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Applying the Patuxent Landscape Unit Model to human dominated ecosystems: the case of agriculture

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Abstract

Non-spatial dynamics are core to landscape simulations. Unit models simulate system interactions aggregated within one space unit of resolution used within a spatial model. For unit models to be applicable to spatial simulations they have to be formulated in a general enough way to simulate all habitat elements within the landscape. Within the Patuxent River watershed, human dominated land uses, such as agriculture and urban land, are already 50% of the current land use, while urban land is replacing forests, agriculture and wetlands at a rapid rate. The Patuxent Landscape Model (PLM) with the Patuxent General Unit Model as core (Pat-GEM) was developed as a predictive policy tool to estimate environmental impacts of such land use changes. The Pat-GEM is based on the General Ecosystem Model (GEM) developed by [Ecol. Modelling 88 1996 263]. Previous calibrations of the Pat-GEM for anthropogenic land uses have not been satisfactory due to the scarcity of appropriate data. This paper shows Pat-GEM simulations of biomass growth and nutrient uptake for crops typical within the Patuxent watershed. The Pat-GEM was expanded to include processes and fluxes that characterize agricultural land use. The most important extension was to include crop rotation into the model. Additionally, we refined the processes for planting, harvesting and fertilization by introducing specific growth parameters. Our revised Pat-GEM was calibrated against the results from Erosion Productivity Impact Calculator (EPIC) a widely used and calibrated agricultural model. We achieved high correlation between results generated with Pat-GEM and EPIC. The correlation coefficients (r^2) varied between 0.87 and 0.98, with the simulation results for winter wheat showing the lowest correlation coefficients. Intercalibration using EPIC is a powerful method for calibrating the Pat-GEM model for agricultural land use. EPIC was able (a) to provide about 30% of the input data required for running the Pat-GEM model; and (b) to provide time series output data (with a daily time step) to calibrate the output variables biomass production and nutrient uptake.

Keywords: Ecosystem models; Agricultural models; Intercalibration; EPIC; Pat-GEM

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1. Introduction

Non-spatial dynamics are core to landscape simulations. Unit models simulate system interactions aggregated within one space unit of resolution for use within a spatial model (Boumans et al., 2001). For unit models to be applicable to spatial simulations they have to be formulated in a general enough way to simulate all habitat elements within the landscape. In this paper, we present the development and validation of a unit model for agricultural land use within the Patuxent landscape. The Patuxent General Unit Model (Pat-GEM) is based on the General Ecosystem Model (GEM) developed by Fitz et al. (1996).

The Patuxent Landscape Model (PLM) aims to be a tool for evaluating landscape change within the Patuxent River watershed through simulation of ecological systems. PLM is a process based, spatially explicit, landscape model of the 2500 km^2 Patuxent River watershed and is designed for the systematic analysis of the interactions among physical and biological dynamics that are conditioned by regional socioeconomic behavior (Costanza et al., 2002). A companion economic model estimates land development patterns based on human decisions using site characteristics, ecosystem properties, and regulatory paradigms as explanatory variables (Bell and Bockstael, 1997).

Within the Patuxent River watershed, human dominated land uses, such as agriculture and urban land use cover about 50% of the total area (Table 1). Agriculture differs from natural land uses in that human interventions determine to a large extent the mass and element flows (e.g. nitrogen, phosphate, and some trace elements). Even though crop growth per se is a biological process, humans choose which crops are to be planted and when they are planted and harvested. In addition, humans manage growth conditions through crop rotation, tillage, fertilizers and pesticide use. To simulate agricultural land uses, the PLM needed to be expanded to include processes and fluxes that characterize this land use.

Agricultural models, contrary to ecosystem models, are oriented towards obtaining maximum yield and most commonly investigate the effect of fertilizers, pesticides, and management practices on crop productivity. They can be divided into three groups: (i) Models, such as the Nitrogen Crop Response Model (NCRM; http://www.qpais.co.uk/nable/nitrogen.htm) and the model for the crop-pathosystem rice-bacterial leaf blight and sheath blight (Reddy, 1994), study crop growth within a geographic region or the impact of specific growth parameters. (ii) Models such as the Soil and Water Assessment Tool (SWAT; Srinivasan et al., 1998) and Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS; Knisel, 1980) assess the impact of agricultural management practices on water quality in a watershed. (iii) Models such as the Erosion Productivity Impact Calculator (EPIC; Sharpley and Williams, 1990) and Erosion Prediction Model (WEPP, Elliot, 1988; Elliot et al., 1989), are integrative models to link crop growth, erosion and other environmental impacts to watershed specific parameters and management practices. As a general rule, agricultural models do not take into account the relationships between agricultural land use and adjacent ecosystems.

Only a few agricultural models, group 2 and 3, include the interaction among management practices, erosion, crop growth, and environmental impact in their analyses, however, they do not consider the interrelationship between agricultural land use and other ecosystems affected by it. Ecosystem models are not usually applied to agricultural land uses because of the large and specialized data requirements. Even though several

Table 1
Characteristics of land use in the Patuxent River catchment area in 1990 and 1994 (data in percentage. Total area: 2356 km^2)

	1990 (%)	1994 (%)	Change 1990–1994 (km^2)
Forest	43	42	24
Agriculture	28	27	24
Residential	18	20	48
Water	6	6	–
Other	5	5	–
Total	100	100	96

Data may not add to 100% because of rounding. Source: Maryland Department of Agriculture (1966, 1972, 1977, 1981, 1986, 1991, 1996).

new tools are available to overcome the data problem (e.g. remote sensing data, which allow for testing the landscape model for rates of biomass production; Birky et al., 2002), new options for achieving an appropriate calibration of ecosystem models are needed.

In this paper, we explore the use of agricultural models for providing data to calibrate ecosystem models. The objective of this paper is to model agricultural land use within the Patuxent watershed using Pat-GEM while providing confidence through inter-calibration with EPIC.

The main questions we address are:

1) Can the Pat-GEM model adequately simulate agricultural land use?
2) How, given the constraints in data availability, can it best be calibrated?
3) What are the most sensitive parameters within the Pat-GEM model describing agricultural land use?

2. Description of the study area

The Patuxent River is one of Maryland's major tributaries to the Chesapeake Bay. Historical data from 1936 up to 1988 have shown increased nutrient concentrations, algae growth, decreased water column transparency and extended oxygen depletion in the lower Patuxent estuary as well as in the Chesapeake Bay. The origins of pollution are largely non-point sources such as nutrient run off from agriculture and pollution from septic tanks in low-density residential areas. The State of Maryland participated in a multi-state federal Chesapeake Bay Program with the aim of reducing nutrient fluxes to this Bay by 40% in the year 2000. A major focus of the program to restore the water quality of the Bay involves a 'tributary strategy' in which the sources of pollutants are estimated for each tributary watershed.

The catchment area of the Patuxent River lies completely within the State of Maryland including parts of Anne Arundel, Calvert, Charles, Howard, Montgomery, Prince George's and St. Mary's Counties. In 1994, the land use in the area was 42% forest, 28% agriculture, 20% residential (low, medium, and high), 6% water and 6% other uses (Table 1). From 1990 to 1994 residential use increased by 2% of the total area (48 km^2) and agricultural and forested areas decreased by 1% each (23 km^2) (Maryland Department of Agriculture, 1966, 1972, 1977, 1981, 1986, 1991, 1996).

The traditional land covers in the watershed have been agriculture and forest. About 70% of the soils are high quality agricultural soils, with moderate slopes (0–5%) and good permeability. The land plots are usually large, which allows for highly mechanized agriculture. On steeper slopes (30% of the land, 28% have a slope of 5–10 and 2% a slope > 10%) soils are still adequate for agriculture, however, because of increasing erosion potential they should be used for orchards rather than heavy tillage crops. Most of the soils in the area are also adequate for low-density urbanization utilizing shallow subsurface septic tanks (Maryland Department of State Planning, 1973).

2.1. Development of agriculture in the area

Comparisons for the period between 1965 and 1995 show three major changes in agriculture:

1) Total agricultural area used for 'traditional' agriculture (corn, hay and tobacco) decreased by 25% from 100 ha in 1965–1975 ha in 1995 (Maryland Department of Agriculture, 1966, 1972, 1977, 1981, 1986, 1991, 1996). A similar pattern has been observed for the acreage of commercial fruit production, which has decreased in the State of Maryland by 40% from 1980 to 1992. In the study area, in 1992, the acreage devoted to fruit production was about 0.2% of the acreage used for traditional crops.
2) Within the above-mentioned changes, land has been reallocated away from corn, hay, and tobacco production to soybeans and wheat production (Fig. 1). In 1995, corn, soybeans, wheat, and hay made up 90% of the cultivated area.
3) With the increasing pressure to reduce pollution from non-point sources such as agriculture, in 1990, the state of Maryland began a program providing technical assistance to

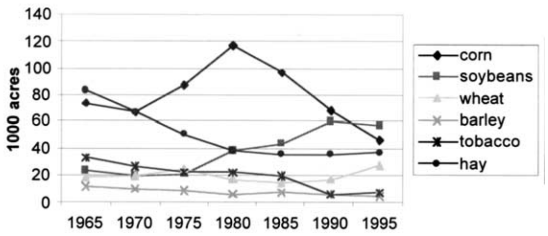

Fig. 1. Agricultural production in the counties located in the Patuxent River catchment area (1965–1995). Commercial fruit and vegetable production were excluded. Source: Maryland Department of Agriculture (1966, 1972, 1977, 1981, 1986, 1991, 1996).

farmers in order to implement nutrient management plans and best management practices. The goal of the nutrient management plan was to design specific fertilization plans for each farm depending on soil fertility, soil type, and crop type. From 1990 to 1997 about 35% of the total productive area of the counties in the Patuxent River watershed were covered by nutrient management plans (Patricia Steinhilber, personal communications, 1998). The development of nutrient management plans is almost homogeneously distributed among the counties, with St. Mary having the largest percentage of planned area and Howard County the smallest. Among the best management practices promoted are conservation tillage techniques and the use of cover crops. According to the Patuxent River Tributary Team, in 1994, farmers were applying conservation tillage techniques on about 15 000 acres (target: 18 000), and use cover crops on 225 acres (target: 11 000).

3. Methods

3.1. Characteristics of the PLM unit model (Pat-GEM)

Pat-GEM includes modules for hydrology, nutrient movement and cycling, terrestrial and estuarine primary productivity, and general consumer dynamics (Fig. 2). The hydrology module of the unit model is a fundamental component for other modeled processes, simulating water flow vertically within the cell (e.g. infiltration, evapotranspiration). Phosphorus and nitrogen are cycled through plant uptake and organic matter decomposition, with the latter simulated in a sediment/soil dynamics module. The macrophyte module includes plant growth response to various environmental constraints (including water, light and nutrient availability and seasonal temperatures), changes in leaf canopy structure (influencing water transpiration), mortality and translocations of photosynthetic product. The principal dynamics modeled in Pat-GEM are:

- Plant and phytoplankton growth in response to available sunlight, temperature, nutrients, and water.
- Animal (consumers) growth in response to food sources.
- Dynamics in detrital matter.
- Dynamics in soil organic matter.
- Flow of water plus dissolved nutrients in three dimensions.

Feedbacks among the biological, chemical and physical model components are important structural attributes to the model. While the unit model simulates ecological processes within a unit cell, horizontal fluxes link the cells together across the landscape to form the full landscape model. These spatial fluxes are driven by cell-to-cell head differences of surface and ground water in saturated storage. Water fluxes between cells carrying dissolved and suspended materials and determining water quality in the landscape.

3.2. Adaptation of the Pat-GEM to agricultural land use

We extended Pat-GEM with algorithms that allowed for simulating crop rotation over a 2-year period. The crop rotation: corn, winter wheat, and soybeans is modeled as follows: first, corn is planted, fertilized, and harvested. After corn cultivation the nutrient and organic matter contents in the soil have changed. In addition, residues are left on the soil, which will provide nutrients for the next crop via mineralization. When modeling

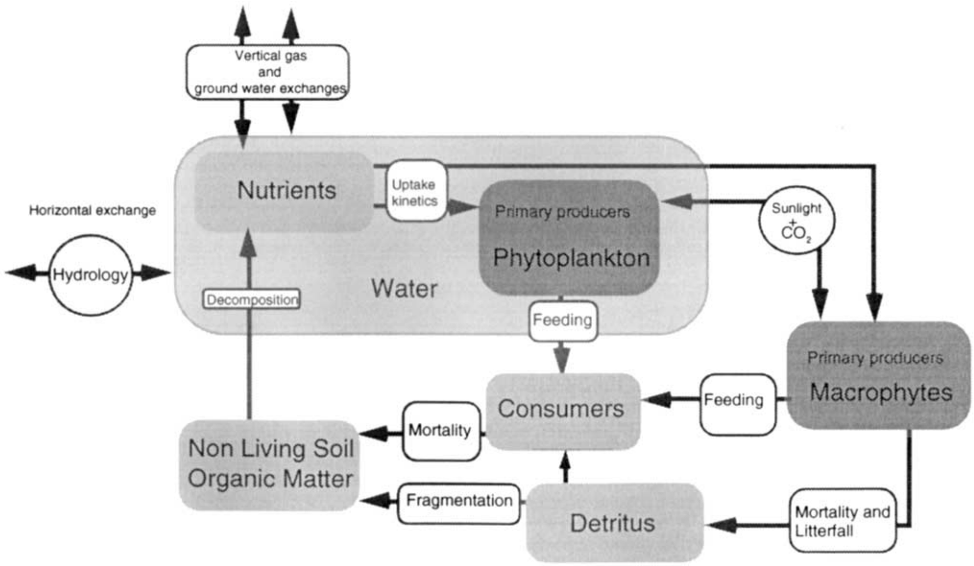

Fig. 2. Material flows between ecosystem components as modeled within a Pat-GEM unit. Source: Boumans et al. (2001).

winter wheat, we use the final values for soil, detritus and organic matter of the corn simulation as initial values for the winter wheat simulation. The same procedure is used for winter wheat followed by soybeans.

In addition, we added parameters to account for human choices in the Pat-GEM macrophyte, nitrogen, and phosphate module. The macrophyte module was extended with decision algorithms on planting and harvesting time and crop growth parameters. In the nitrogen and phosphate module, fertilizer application was included.

3.3. Selection of an agricultural model for intercalibration

For the selection of the agricultural model for intercalibration we had the following criteria: (i) the model had to be well established, that is, it had been validated and tested for different areas. Ideally, also sensitivity analyses and error margins should be available; (ii) the model should operate at the same scale as the Pat-GEM model, that is, on plot size level, (iii) the model should include a crop growth module for different crops, a nutrient cycling module and an erosion and runoff module. The latter does not necessarily have to be at a regional scale, as the regional scale is included in the landscape model.

Given those criteria only three models were considered for closer evaluation: EPIC, WEPP and CREAMS (Table 2). EPIC was chosen, because it is the only model that operates on a plot level, includes crop growth, nutrient cycling and erosion and runoff modules.

3.4. The EPIC model

EPIC is an agricultural land use model, developed to analyze the relation between erosion and productivity (Sharpley and Williams, 1990; Mandel, 1997). It assesses the combined impact of management decisions on soil loss, water quality, and crop yields. It is designed for long-term simulations of about 50/100–500/1000 years. EPIC is composed of a physical based component that simulates erosion, plant growth and related processes and an economic component for assessing production costs and revenues. The physical component includes hydrology, weather, erosion (water and wind), nutrient cycling, crop growth, management practices and plant environmental control (for detailed information see Sharpley and Williams, 1990).

Table 2
Comparison of different models for intercalibration of ecosystem models

	EPIC	WEPP	CREAMS
Principal application	Loss of crop yield due to erosion	Erosion prediction	Water quality analyses for field sized areas
Established (error margins, validation)	Yes	Yes	Yes
Scale	Plot size	Watershed	Watershed (= field)
Crop growth module	Yes	Adapted from EPIC	Partly included
Nutrient cycling module	Yes	Not included	Partly included
Erosion and runoff	Yes (on plot level)	On watershed level	On watershed level

EPIC crop growth simulates energy interception and conversion to plant structures such as roots, aboveground biomass, grain or fibers, under constraints of water and nutrient availability, and air temperature stresses.

EPIC simulates nitrogen (N) and phosphorous (P) fluxes. The N fluxes modeled are fixation, wet deposition, crop uptake, runoff of NO_3^-, organic-N transport by sediment, NO_3^- leaching, upward NO_3^-N movement by soil water evaporation, denitrification, immobilization, and mineralization. The N mineralization and immobilization models, are based on the PAPRAN model (Seligman, 1981). The P fluxes are runoff of soluble P, sediment transport of mineral and organic phosphorous, immobilization, mineralization, sorption–desorption, and crop uptake (Sharpley et al., 1990).

Already existing EPIC input files for hydrological catchment areas within the Chesapeake Bay in Maryland were adapted to the crop rotation and management practices typically recommended and practiced in a large percentage of the agricultural area of the Patuxent River watershed (Reed, personal communication, 1998). The output data of the EPIC runs and the Pat-GEM results were calibrated against regional crop harvest data.

3.5. Intercalibration

Intercalibration (model calibration against results of a separate independent model) requires:

- Confidence in the output of the reference model.
- The reference model output for the area of interest to be available within similar temporal and spatial scales.
- The output of the reference model to be compatible to output of the model to be calibrated.

EPIC was considered appropriate for intercalibrating the Pat-GEM because (i) EPIC has been calibrated and tested for different states in the USA during the last 20 years (Sharpley and Williams, 1990; Kiniry et al., 1990) including Maryland (Mandel, 1997); (ii) EPIC and Pat-GEM both, have similar temporal and spatial resolutions. Both models generate a daily output and have spatial resolutions in the range from 1 to 4 ha, assuming homogenous soil characteristics and management practices and (iii) the output data of EPIC are relevant for the data to be calibrated in the Pat-GEM.

Even though the method of intercalibration helps to overcome the lack of data, some output data of the reference model might reflect model artifacts. In order to recognize the latter, the output data of the reference model have to be carefully tested, the model structure has to be understood, and plausibility analyses have to be made.

We intercalibrated the Pat-GEM model for each individual crop separately, considering as starting values the end values of the cultivation period of the crop cultivated beforehand. In the intercalibration procedure, we focused on fluxes relevant to nutrient management. We made initial estimates of nutrient balances from EPIC output for the agricultural setting shown in Table 3, through material flux analysis (MFA, Baccini and Bader, 1996).

3.6. Agricultural nutrient flows in the Patuxent River watershed

Calibrating Pat-GEM nutrient fluxes with first adjusting crop biomass growth and nutrient uptake, and second, through run off of soil (erosion) and nutrients is warranted as first model simulations suggest that:

1) Mineralization of plant residues accounts for 45% (N) and 60% (P) of the total input into soil, while additional fertilizers account only for 35% (N) and 40% (P) in corn and wheat and soybeans fixate an additional 20% of the total N-input into soil.
2) Nutrient uptake by plants accounts for about 95% of nutrient losses from soil. The rest of the output of soil is divided into nutrient loss with sediments (around 4%) and others (see Fig. 3).

Table 3
Description of the agricultural setting used for calibration of the Pat-GEM model

Date	Activity	Amount (kg/ha)
May 10	Plant corn	
May 10	Fertilize N	72.86
May 10	Fertilize P	24.66
June 10	Fertilize N	72.86
October 15	Harvest Corn	
October 20	Plant winter wheat	
October 21	Fertilize N	16.81
October 21	Fertilize P	19.73
February 20	Fertilize N	50.44
March 20	Fertilize N	50.44
July 5	Harvest winter wheat	
July 10	Plant soybeans	
November 14	Harvest soybeans	

Source: Reed (personal communication, 1998).

These results suggest that we have to focus on the calibration of biomass growth and nutrient uptake by crops.

For intercalibration we first selected the Pat-GEM parameters with the largest influence on the fluxes and stocks determined in the MFA. These parameters were adjusted to achieve the best fit between the output data of Pat-GEM and EPIC (see Section 4).

3.7. Calibration procedure

3.7.1. Data sources for input parameters

Soil data was provided by the Maryland Office of Planning; weather and hydrological information was obtained from the USGS Water Resources Information web site. Input parameters referring specifically to the models dynamics were taken from the EPIC database (54%), personal communications of experts (14%), literature values (18%) or were estimated (14%). EPIC provided most of the data related to crop characteristics and crop growth. Data related to modules other than

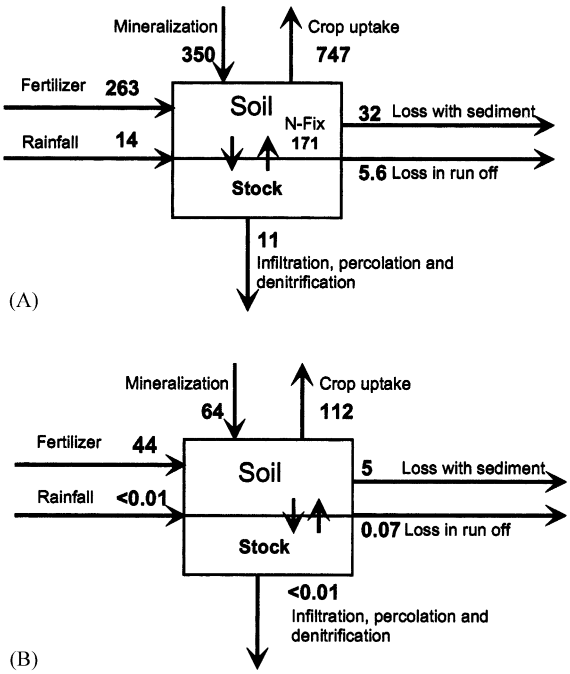

Fig. 3. Nitrogen (A) and phosphorous (B) balances for the land use agriculture in kg/ha (data: EPIC base run).

macrophyte, nitrogen, and phosphate modules, were obtained from literature and the rest had to be estimated (for details see Table A1).

3.7.2. Agricultural settings for calibration

We intercalibrated the Pat-GEM for the 2-year crop rotation, corn, winter wheat, soybeans using a low till system. This crop rotation and management practices are typically recommended and practiced, with little variation, in a large percentage of the agricultural area of the Patuxent River watershed (Reed, personal communication, 1998). In the selected setting, corn is planted around May 10, and immediately fertilized with nitrogen and phosphorous. About 1 month later a second fertilization only with nitrogen is performed. In October, corn is harvested (the exact date depends on whether corn is used for silage or for animal feeding), and shortly thereafter winter wheat is planted with a chisel plow within the corn stubble. Winter wheat is fertilized with nitrogen and phosphorous immediately after planting and again with nitrogen in February and March of the following year. After the winter wheat harvest in early July, soybeans are planted. Soybeans are usually not fertilized (for some soils fertilization with phosphorous is recommended). Soybeans are harvested in November. Thereafter the fields are left uncovered until May of the following year, when corn is planted again (Table 3).

3.7.3. Output data sources

The output data for calibration were divided into time series data for time series calibration and benchmark data for plausibility tests. Time-series calibrations were performed using the daily EPIC output data, which had an error margin of 7–10% or lower (see Table 4). For performing plausibility tests, we used EPIC output data with error margins higher than 10% and literature data. The time series data sets included daily data for biomass growth and nutrient uptake.

Table 4
EPIC output data used for calibration and correspondent Pat-GEM output variables for time series calibration

Sector	Parameter
EPIC model	
Crop growth	Biomass
Nutrient cycling	N uptake by plants
	P uptake by plants
Pat-GEM model	
Macrophyte	Mac_tot_biom
DIN sector	DIN_sew_uptake
PO_4 sector	PO4_sew_uptake

4. Results and discussion

4.1. Simulation of agricultural land use with the Pat-GEM model

Pat-GEM was able to simulate biomass growth and nutrient uptake of the corn, winter wheat and soybeans rotation well. Statistically, the simulation error was lowest for biomass growth (correlation between EPIC and Pat-GEM output data r^2: 0.96–0.98). For nutrient uptake the r^2 ranged from 0.88 to 0.98 (Figs. 5 and 6 for corn[3]).

4.1.1. Biomass growth

In both models biomass growth presents a logistic growth curve, even though biomass growth is modeled differently in both models (see sensitivity analysis). For the three crops the largest difference between both models lies in the start of the exponential growth phase. In the case of corn ($r^2 = 0.975$), the exponential growth phase in the Pat-GEM simulation is shifted by about 10 days with respect to the EPIC data set, but the growth rates are similar (Fig. 4). In the case of soybeans ($r^2 = 0.976$), the exponential growth rate is slightly lower with EPIC then in the simulation.

4.1.2. Nitrogen uptake

For corn ($r^2 = 0.919$) and winter wheat ($r^2 = 0.933$) the EPIC data showed a higher nitrogen uptake in the early and exponential growth phase then the Pat-GEM simulation (see Fig. 5 for corn) because Pat-GEM nutrient uptake is linearly linked to biomass growth via a fixed N/C ratio. Thus, the nutrient uptake curve has the same

[3] All figures are available upon request.

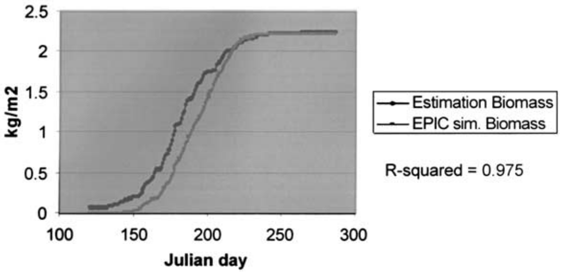

Fig. 4. Comparison between the estimated biomass and the EPIC simulated datasets for corn (kg/m^2).

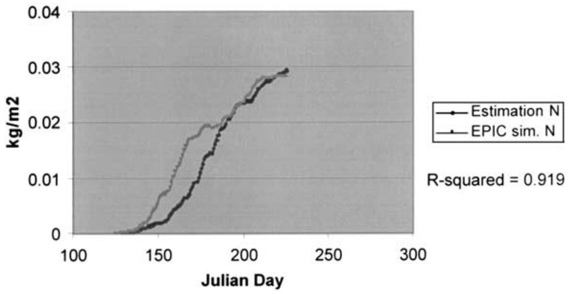

Fig. 5. Comparison between the estimated nitrogen uptake (Pat-GEM model) and the EPIC simulated datasets for corn (kg/m^2).

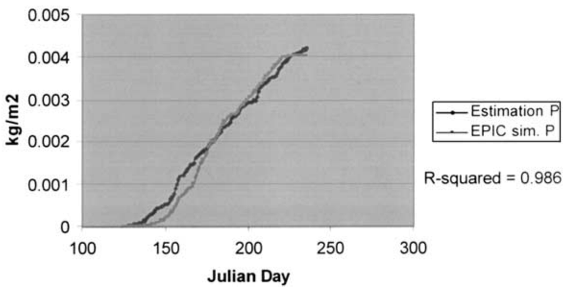

Fig. 6. Comparison between the estimated phosphorous uptake (Pat-GEM model) and the EPIC simulated datasets for corn (kg/m^2).

shape as the biomass growth curve as long as sufficient nitrogen is available. In the EPIC model, however, nitrogen uptake is modeled using a supply-demand function. The N demand is the difference between the N content in the crop and the ideal N content for each day. Thus, the N demand is a function of biomass, optimal N concentration, and N already taken up. The optimal concentration changes with time, being largest in the emergence stage and lowest in the maturity stage (Sharpley and Williams, 1990).

The Pat-GEM model N/C ratios are similar to the average N concentration during the lifetime of a plant in the EPIC model (Table 5). In the case of corn and winter wheat the differences between emergence and the average value are higher (in percent) than in the case of soybeans. This explains why in the early stages of growth the EPIC data show a higher N uptake than the estimated data[4].

These differences do not play a significant role concerning the yearly element balance. However, they might influence the simulated N-fluxes to surface water, if N introduced into the soil by fertilization is rapidly taken up by the plant in the case of the EPIC model and surplus N would be washed off in the case of the Pat-GEM model.

4.1.3. Phosphorous uptake

The P uptake curves for corn ($r^2 = 0.975$) and soybeans ($r^2 = 0.974$) are very similar to the biomass growth curves (Fig. 6 for corn). In the case of winter wheat, the correlation between the data sets is not very satisfactory ($r^2 = 0.877$). The EPIC data set presents a non-homogenous phosphorous uptake. During wintertime, due to low temperatures, phosphorous uptake is limited in EPIC. However, as soon as temperature rises, phosphorous becomes more available and large uptake rates occur. In contrast, in the Pat-GEM due to a constant P/C ratio, P uptake is directly linked to biomass growth and thus occurs in the form of a logistic growth curve.

In both models, phosphorous uptake is modeled similarly to nitrogen uptake, i.e. in the Pat-GEM; phosphorous uptake is proportional to biomass growth. The comparison of the P concentrations in the crop during the different growth stages in the EPIC model (Table 6) with the P/C ratio in the

[4] The case of winter wheat is somewhat special because in the EPIC model nutrient uptake seems to stagnate in some parts during the growth of the plant. This could also be an artifact of the EPIC model, which assumes that nutrient uptake cannot occur beyond the maximal N/P concentration during a certain period of growth (Benson, personal communications, 1998).

Table 5
Comparison of N concentration in the different stages of growth according to the EPIC model and calibrated N/C ratios in the Pat-GEM model

Crop	Emergence	Mid-time	Final growth stage	Average value EPIC	Pat-GEM calibrated value
Corn	0.044	0.0164	0.0128	0.0243	0.028
Winter wheat	0.06	0.023	0.0134	0.0321	0.028
Soybeans	0.0524	0.0265	0.0258	0.0349	0.0468

Table 6
Comparison of P concentration in the different stages of growth according to the EPIC model and calibrated P/C ratios in the Pat-GEM model

Crop	Emergence	Mid-time	Final growth stage	Average value EPIC	Pat-GEM calibrated value
Corn	0.0062	0.0023	0.0018	0.0034	0.004
Winter wheat	0.0084	0.0032	0.0019	0.0045	0.0025
Soybeans	0.0074	0.0037	0.0035	0.00486	0.0038

Pat-GEM model shows that for corn and soybeans the average concentration value in EPIC is similar to the Pat-GEM calibrated P/C ratio. In the case of winter wheat, however, the Pat-GEM calibrated P/C ratio is significantly lower than the EPIC average P concentration.

4.2. Constraints in data availability for the Pat-GEM model

In Section 3.7, we described the data sources for the Pat-GEM input data. It can clearly be seen that the EPIC model provides a large amount of the Pat-GEM input data. But because the models have a different structure and modeling basis, about 18% of the input data needed to be found in the literature[5]. However, due to the combination of both sources only 14% of the input data had to be estimated.

4.3. Sensitivity analysis

Sensitivity analysis studies the sensitivity of a dependent variable with respect to specific variations of the parameters (or independent variables). It allows for quantifying the effect of a defined parameter change on a variable. We used sensitivity analysis to (i) understand which parameters drive the Pat-GEM model; and (ii) comprehend how a new crop can be modeled with Pat-GEM. For the sensitivity analysis the calibrated parameter values were varied by 20%. The impact of this 20% change on biomass growth, P and N uptake was quantified.

4.3.1. Biomass growth

In the Pat-GEM the following parameters were critical for modeling biomass growth of the different crops (Pat-GEM model):

- minimum daylight requirement for sprouting in h/day (mac_dl_rq);
- net primary productivity per day (NPP);
- maximum ratio of photosynthetic biomass to non-photosynthetic biomass in mature system (max_ph_t_Abm);
- weight of the plant non-photosynthetic part at planting (mac-planting weight);
- maximum above ground biomass in kg/m^2 (max ab BM).

These parameters are at the same time the ones that differ most among the three crops (Table A2).

[5] Pat-GEM being an ecosystem model includes also a consumer module (Fig. 2) and uses growth parameters different than the ones in EPIC.

The parameters influence biomass growth at different growth stages, i.e. emergence until half growth time and total biomass at the end of biomass growth. Therefore, new crops can be modeled by calibrating these parameters.

4.3.1.1. Emergence until half growth time. The most sensitive parameters in this growth stage are daylight requirement for sprouting, net primary productivity (NPP) and initial weight of seeds. A 20% increase in the daylight requirement for sprouting inhibits growth of corn and soybeans (Table 7). Winter wheat growth is not influenced by a 20% change in this parameter. The growth rate is regulated by NPP, which shifts the growth curve to the right or to the left. A 20% change in NPP doubles or triples biomass in early growth stages. NPP has, however, no effect on the total biomass produced. A 20% of change in the initial weight of planting affects the growth of corn more in the first quarter of growth (−10 and 30%), winter wheat (−15 and 26%) and soybeans (−19 and 16%) until half growth time.

4.3.1.2. Total biomass. Total biomass is sensitive to the parameters maximum above ground biomass and potential in photosynthetic biomass in relation to the total above ground biomass. The first parameter has a proportional effect on total biomass. A 20% change in maximum above ground biomass leads to a 20% increase or decrease in total biomass. The effect of the potential in photosynthetic biomass in relation to the total above ground biomass is about half as large: A 20% change leads to an 8, 10 or 16% change in total biomass of soybeans, corn and winter wheat, respectively.

In EPIC, the most sensitive parameter is daily heat units accumulation (in contrast to the Pat-GEM model, where day length requirement is limiting). A crop starts growing, when the daily temperature exceeds the crop specific base temperature. Biomass growth is adjusted if one of the five plant stress factors, water, temperature, nutrients, aeration or root growth is limited.

For modeling biomass growth of crops such as corn and soybeans, which grow during spring and summer, the different modeling approaches do not affect the results significantly, while for winter wheat the difference leads to different growth and nutrient uptake rates. Thus, one could optimize Pat-GEM to better simulate winter wheat growth by making NPP, for example, temperature dependent.

4.3.2. Nitrogen and phosphorous uptake

The parameters in the Pat-GEM model that had the largest influence on nitrogen and phosphate uptake of plants were (in brackets: name in Pat-GEM model):

- N/C and P/C ratio of photosynthetic biomass (PhBio NC and PhBio PC) and;
- maximum concentration of phosphate in non-adsorbed soil phosphate in g/l (PO_4 crit conc.).

As for biomass, these parameters vary from crop to crop (Table A3). The N/C or P/C ratio of photosynthetic biomass indicate that N and P are taken up in a constant ratio to the biomass over the whole period of growth. For nitrogen a 20% change in the parameter N/C ratio leads to a 20% change in nitrogen uptake. In the case of phosphorous the effect of this parameter varies from crop to crop and is not proportional (Table 8). For corn a decrease of 20% in the P/C ratio leads only to a 6% decrease in the final content of phosphorous in the crop, while for soybeans a 20% decrease in the P/C ratio leads to a 20% decrease in the total phosphorous uptake. This lower impact of P/C ratio on phosphorous uptake (compared with nitrogen) can be explained as follows: in comparison to nitrogen uptake, phosphorous uptake is additionally regulated as a slow release mechanism by a soil dependant critical equilibrium in concentrations between dissolved and absorbed phosphors in the soil. This critical equilibrium concentration in dissolved phosphorous per quantity of soil is reduced by plant uptake and replenished from the absorbed phosphorous when available. This parameter regulates the dissolved phosphorous in soil, which is available for uptake. Its value varies from crop to crop due to organic matter concentration and clay content associated with each soil type. The parameter maximum concentration in non-adsorbed soil

Table 7
Sensitivity analysis for biomass

	Minimum daylight required for sprouting (h/day)		Net primary productivity (per day)		Potential in photosynthetic biomass in relation to total above ground biomass		Initial weight of the plantings or seeds (kg)		Maximum above ground biomass (kg/m^2)	
	−20%	**+20%**	**−20%**	**+20%**	**−20%**	**+20%**	**−20%**	**+20%**	**−20%**	**+20%**
Corn										
25% growth	18	**−83**	−28	**65**	−28	**58**	−13	30	−8	8
50% growth	5	**−96**	−26	18	−28	24	−4	7	−14	16
75% growth	0	**−97**	−4	0.5	−11	9	0	0.5	−20	20
100% growth	0	**−97**	−0.5	0	−9	8	0	0	−20	20
Winter wheat										
25% growth	0	0	−25	33	−25	**42**	−17	25	0	0
50% growth	0	0	**−45**	**61**	**−46**	**79**	−13	27	5	9
75% growth	0	0	−33	18	−35	27	−3	9	−13	19
100% growth	0	0	−12	2	−16	11	−1	1	−19	20
Soybeans										
25% growth	0	**−60**	−20	20	−20	20	−20	20	0	0
50% growth	0	**−93**	**−43**	38	**−48**	**43**	−18	13	−7	3
75% growth	0	**−96**	−8	1	−14	8	−1	0	−20	19
100% growth	0	**−96**	−1	0	−8	7	0	0	−20	19

The parameters were varied by 20%. The change of biomass at different growth stages is shown in percent. Bold, changes in biomass growth, which are more than double the changes in the parameters.

Table 8
Sensitivity analysis for nitrogen and phosphorous uptake

	Nitrogen–carbon ratio		Phosphorous–carbon ratio		Maximum concentration in non-adsorbed soil phosphate (g/l)	
	−20%	+20%	−20%	+20%	−20%	+20%
Corn						
25% growth	−20	20	−15	8	−3.7	3.6
50% growth	−20	20	−5	4	−5.8	5.7
75% growth	−20	20	−6	4.4	−5.7	5.6
100% growth	−2	20	−6	4.7	−5.6	5.5
Winter wheat						
25% growth	−20	20	−20	20	0.0	0.0
50% growth	−20	20	−11	9	−8.4	7.2
75% growth	−20	20	−6	4.7	−12	11
100% growth	−20	20	−7	5.4	−11	10
Soybeans						
25% growth	−20	20	−20	20	0	0
50% growth	−20	20	−20	19	0	0
75% growth	−20	20	−20	13	−4.5	0
100% growth	−20	20	−20	14	−4.4	0

The parameters were varied by 20%. The changes of N and P uptake at different growth stages are shown in percent.

phosphate, thus reduces the sensitivity of phosphorous uptake on a change in the P/C ratio on.

In EPIC nitrogen and phosphorous uptake are regulated via the demand of the plant, which changes during the different periods of growth (Tables 4 and 5). The N and P demand are dependent on biomass, and the optimal concentration of N, P in the crop at each growth stage (note that the optimal concentration of N, P in the crop declines with increasing growth stage; Sharpley and Williams, 1990). N and P uptake are calculated at each daily time step.

4.4. Advantages and problems of intercalibration of ecological process models

The method of intercalibration is a powerful tool for overcoming the lack of data necessary for calibrating process based ecological models for agricultural land use. In addition, basic input data can be borrowed from agricultural models.

Intercalibration also offers additional insight into the processes that are implied in the more aggregated and data driven agricultural models and modeling procedures. Thus, the ecological process model can be easily complemented with the necessary algorithms for agriculture.

However, also some problems might arise when using intercalibration. Results from agricultural models as from any other model have an error margin. That is, the data is not as accurate as field measurements might be, which obviously also have error margins. If the model is, however, used for evaluation of different scenarios of land use, the results will indicate, in which direction N or P contamination of the Patuxent River might occur. As the results have the same error margins, the relative changes can be predicted quite well, while predictions in absolute values might have to be interpreted more carefully.

Another problem of intercalibration is that the reference model might produce results that could be model artifacts. In this case, a good knowledge of the reference model and a close cooperation with the developers of the model is indicated.

5. Conclusions

1. This paper showed that the Pat-GEM model can be adapted for simulating agricultural land

use. The r^2-values obtained by comparing the estimated data sets and the reference data sets for biomass growth and nutrient uptake were in the range of 0.877–0.98, with biomass growth showing the best correlation.

2. The method of intercalibration is a powerful tool for overcoming the lack of data necessary for calibrating process based ecological models for agricultural land use. To perform an intercalibration the reference model has to have the following characteristics: (i) the reference model has been calibrated and tested and for similar geographical areas over long periods of time. (ii) The calculation algorithms have to be at the same resolution of time and space. (iii) The output data of the reference model have to be relevant to the model and/or model sectors to be calibrated. (iv) The structure of the reference model has to be well understood in order to be able to identify model artefacts.

With sensitivity analysis we identified the eight most important parameters in the Pat-GEM model, which differ among the three crop types studied. By changing these parameters, Pat-GEM can be adapted to model additional crop types.

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Appendix A

Table A1: Input parameter values and sources (data are for corn).

Parameter	Value	Source	Comments
Cons_assim	0.25	Estimate	
Cons_ic	0.002 kg/m^2	Based on Brady and Weil, 1996	Herbivores in 15 cm depth
Cons_max	0.02 kg/m^2	Based on Brady and Weil, 1996	Herbivores in 15 cm depth
Cons_rc_mort	0.01 per day		
Det_to DOM_rc	0.05	EPIC	Cellulose like material
Det_ic	0.25 kg/m^2	EPIC	
Det_shred	0.8	Based on EPIC	
DIN_fert_appl (tot)	7.3 kg/m^2	Reed, 1998 (p.c.)	
DIN_fix	0 kg/m^2 per year	EPIC	Soybeans: 0.00123 kg/m^2 per year
DOM_decomrt	0.0095	EPIC	Lignin like material
DOM_max_depth	2 m	EPIC	
DOM_NC	0.09	Johnson and Lindberg, 1992	
MAC_canopdecoupl	0.6	Based on Jarvis and McNaughton, 1986	
MAC_maxcanopcond	0.01 mol/m^2 per s	Dito	
MAC_maxrough	0.16	EPIC	Chisel plow with residues
MAC_minrough	0.1	EPIC	Chisel plow with residues
MAC_DL_RQ	10 h	Different sources	
MAC_Harverstday	288	Reed, 1998 (p.c.)	
MAC_KS_N	0.00164 g/l	EPIC	
MAC_KS_P	0.0023 g/l	EPIC	
MAC_max_dens	six plants per m^2	Different sources	
MAC_max_ht	2 m	EPIC	
MAC_Plantday	121	Reed, 1998 (p.c.)	
MAC_pl_wt	0.01 (0.0007 cal)	Estimated	
MAC_root_to_heigth	1	EPIC	
MAC_temopt	25 C	EPIC	
MAC_max ab_Bm	1.8 (1.1 cal)	EPIC	
MAC_max_gr_time	0.7 years	EPIC	
MAC_max_ph_t_Abm	0.9 (0.7 cal)	EPIC	
NPHBio_ABVBEL	1.8	EPIC	
NPHBio_prop_harv	0.85	Reed, 1998 (p.c.)	
NPP	0.07 (0.42 cal)	Estimated	
Ph_Bio_NC	0.0128 (0.028 cal)	Based on EPIC	
Phbio_PC	0.0032 (0.004 cal)	Based on EPIC	
PO_4_CtoDOM	0.000825	EPIC	
PO_4_crit_conc	0.03 (9 cal)	Estimated	
PO_4_fert	2.5 kg/m^2	Reed, 1998 (p.c.)	

p.c., Personal communication.
For description of parameter see website.
The values marked with * were assumed to be definitive values.

Table A2: Calibrated values of sensitive input parameters for biomass growth.

Parameter	Units	Calibrated value
Mac dl rq (corn)	h/day	13.8
Mac dl rq (winter wheat)	h/day	8
Mac dl rq (soybeans)	h/day	13
NPP (corn)	Per day	0.42
NPP (winter wheat)	Per day	0.185
NPP (soybeans)	Per day	0.65
Max ph t Abm (corn)	–	0.7
Max ph t Abm (winter wheat)	–	0.65
Max ph t Abm (soybeans)	–	0.45
Mac planting weight (corn)	kg per plant	0.00007
Mac planting weight (winter wheat)	kg per plant	0.0000095
Mac planting weight (soybeans)	kg per plant	0.0009
Max ab BM (corn)	kg/m^2	1.1
Max ab BM (winter wheat)		0.9
Max ab BM (soybeans)		0.6

Table A3: Calibrated values of sensitive input parameters for N and P uptake in plants.

Parameter	Units	Calibrated value
PhBio NC (corn)	–	0.028
PhBio NC (winter wheat)	–	0.028
PhBio NC (soybeans)	–	0.0468
PhBio PC (corn)	–	0.004
PhBio PC (winter wheat)	–	0.0068
PhBio PC (soybeans)	–	0.0038
PO_4 critical concentration (corn)	g/l	9.00
PO_4 critical concentration (winter wheat)	g/l	15
PO_4 critical concentration (soybeans)	g/l	35

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