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Quantitative simulation of biochemical processes in peatlands as a tool to define sustainable use?

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A natural property of mires is their ability to accumulate carbon and nutrients in the form of peat. Drainage and agricultural land use have changed the nutrient balance from accumulation to mobilisation. In this study, the effect of land use and hydrology on nitrogen dynamics is quantified using a GIS-based dynamic modelling approach. In the simulation, the nitrogen budget is controlled by drainage depth, land use type and fertilizer application. Denitrification is, next to harvest, the quantitatively most important output pathway from peat soils with a predominant vertical water flow. Only for the wet *Caricion elatae* type was a net nitrogen accumulation simulated. The spatial visualisation of the nitrogen balance shows a high variability based on the heterogeneity of the peatland. Rewetting and extensivication can reduce the deficit in the nitrogen balance and lead to a slight increase of the accumulating area. These simulation results can be used in environmental planning to define a more sustainable land use in the future.

Key words: restoration, peatland, modelling, nitrogen, denitrification

INTRODUCTION

The wise use of wetlands was defined in 1987 during the third RAMSAR conference in Regina, Canada as "the wise use of wetlands is their sustainable utilisation for the benefit of humankind in a way compatible with the maintenance of the natural properties of the ecosystem (RAMSAR 1987)".

This definition was signed by several governments and the International Peat Society adopted the definition for the wise use of mires in 1998 (IPS 1998). The definition consists of two parts, linked with the adjective 'compatible'. The term 'utilisation for the benefit of humankind' stresses social and economical aspects of mire and wetland use. The ecological aspects are emphasised with the phrase 'maintenance of the natural properties of the ecosystem'.

The most important natural property of mires — fens and bogs — is their ability to accumulate carbon, nitrogen and other nutrients in the form of peat (Clymo 1984, Succow 1988, Gorham 1991, Joosten 1993). The factors affecting peat forming processes range from geomorphologic, climatic, hydrological, to vegetation and micro-

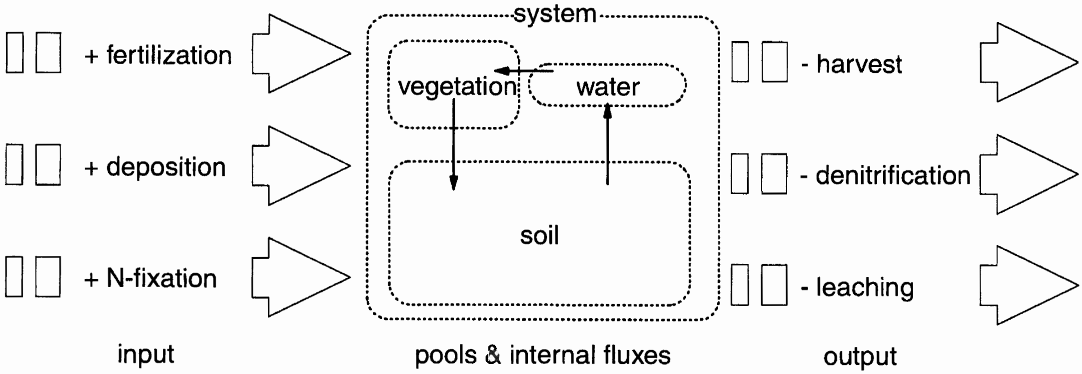

Fig. 1. Conceptual model for pathways and pools in the nitrogen budget.

bial conditions. The actual accumulation rate for a system can be calculated by applying the concept of input–output balances (Fig. 1).

In general, nutrient balances consist of input pathways, like fertilization, nitrogen fixation or atmospheric deposition in the nitrogen cycle. In the system, different pools can be identified: the soil organic nitrogen bound in peat, the water dissolved nitrogen species NO_3-N and NH_4-N and nitrogen bound in the above and belowground biomass. These pools are linked via internal processes e.g. mineralization (nitrification and ammonification), plant uptake and decomposition. In the nitrogen balance, important output pathways include harvesting, nitrogen leaching and denitrification.

In western Europe, the majority of mires are drained and cultivated for agricultural purposes (Succow 1988, Schopp-Guth 1999). These areas have lost their accumulation ability, and can, consequently, only be considered as peatlands. Drainage and cultivation cause high peat loss rates due to shrinkage, compaction and subsidence (Nieuwenhuis & Schokking 1997). The oxidation of the upper peat layer leads to high mineralization rates. On such drained peatlands, the vegetation can take up only a part of the mineralised nitrogen. The rest is either transformed by biochemical processes like denitrification or immobilisation or transported out of the system with surface water and groundwater flow. In general, agricultural land use on drained peat soils is regarded as not sustainable due to high peat loss rates in combination with high environmental impact (Immirzi et al. 1992, Schopp-Guth 1999).

For these drained peatlands, it is necessary to develop land use forms with lower peat loss rates and reduced environmental impact. In this study, the effect of land use on the nitrogen balance is quantified for a single minerotrophic peatland with a simulation approach. The application of a dynamic model for water and nitrogen transformations on a mesoscale with a high spatio-temporal resolution allows:

— the quantification of the output pathways in the nitrogen cycle depending on land use type,
— the identification of factors controlling nitrogen loss and
— the prediction of the effect of land use changes on the nitrogen balance.

MATERIAL AND METHODS

Modelling

The water and nitrogen dynamic of peatland ecosystems is characterised by complex spatio-temporal interactions between soil physical and chemical properties, microbial activities, species abundance, composition of vegetation types, hydrological and climatic conditions. Also anthropogenic disturbance e.g. drainage, fertilization, mowing or grazing influence the structure and function of ecosystems and the interactions between them up to the landscape scale.

These complex interactions can either be quantified by establishing a long-term measuring programme for all important transformation processes and pathways, or by applying a validated, dynamic model system for the water and nitrogen transformation. The model application is, compared with long-term measurements, less expensive, and allows the identification of regulating factors in the water and nitrogen dynamics and the prediction of the effect of possible land use changes on the nitrogen balance (Wali et al. 1999).

The water and nitrogen model WASMOD

In this study, the water and nitrogen dynamics of a minerotrophic peatland, the Pohnsdorfer Stauung in northern Germany, was calculated with the simulation system WASMOD (Water And Substance MODel). The model WASMOD calculates water fluxes as well as carbon and nitrogen transformations of ecosystems dynamically with a high spatiotemporal resolution. The model is described in detail by Reiche (1994, 1996). The primary spatial units are single plots (ecosystems) characterised by the same vegetation, land use, soil properties and hydrological conditions. The soil profile is vertically segmented into 15 soil layers representing the unsaturated and saturated soil zone. The model can be applied for single plots or connected to a Geographical Information System for entire (sub)catchment areas. WASMOD consists of several submodels for transformation and transport processes involving water, heat, carbon, and nitrogen. For some of the processes, theories and mechanisms are well understood while for other processes existing knowledge is still limited. Processes in the water regime include daily measured precipitation as input, interception by plant canopy, infiltration into the upper soil layer, surface runoff, and if infiltration capacity is exceeded, evapotranspiration and seepage. The vertical movement of water in the soil profile is solved by means of a numerical solution for the Richards equation. The soil temperature submodel follows Hoffmann et al. (1993). The one-dimensional heat flow equation is based on the volumetric heat capacity of the soil, thermal conductivity, organic matter content and moisture content as well as soil substrate specific variables. The soil mineral nitrogen processes are coupled with the carbon translocation and turn over processes according to Hansen et al. (1990). Organic matter turnover is modelled by dividing the organic matter conceptually into three main pools: added organic matter of plant residues and manure (AOM), soil organic matter (SOM) and soil microbial biomass (SMB). Each pool of organic matter is divided into two subpools characterised by particular C/N ratio and turnover times resulting in high and low mineralization rates. The soil mineral processes include mineralization of organic nitrogen, nitrification, immobilization, denitrification, plant uptake by roots and vertical movement of nitrate and ammonia in the soil. Denitrification is simulated by defining a potential denitrification rate assumed to be related to the carbon dioxide evolution rate in the soil and the soil temperature. The vegetation is conceptually treated as vegetation type with characteristic annual biomass growth and decay rates, and specific carbon and nitrogen concentrations in the above and belowground biomass. The agricultural system management allows various management options, for example for fertilization or harvest.

For application of the model at the plot scale, most of the input parameters can be measured in the field (Table 1). At the mesoscale, the required input data are calculated using a software package developed for Digital Landscape Analysis and Modelling (DILAMO) (Reiche 1994, Reiche et al. 1999). The spatial interactions between ecosystems are calculated from a high resolution Digital Elevation Model (25 * 25 m grid size) combined with a digital river and drainage network. The soil properties are derived from soil profile descriptions applying validated pedotransfer functions (Reiche 1994). The information about vegetation and land use type can be mapped in the field or obtained from various digital land cover maps.

The model output at the plot scale are time series with a user dependent variable time step from day to week for transformation and transport processes in the water and nitrogen dynamics as well as annual balances for all simulated processes in the water, nitrogen and carbon budget. At the mesoscale, only these last annual process rates are given as output for each spatial unit.

Study area

The model was applied in a small terrestrialisation fen, the 'Pohnsdorfer Stauung' (54°15´North–10°12´East) 10 km southeast of Kiel, Germany. The fen is situated in the catchment area of the "Neuwührener Au" brook, near its outlet in the lake Postsee in the Weichselian moraine landscape. The fen developed between two ice advances in a dead ice depression. After melting of the dead ice in the Late Weichselian, a lake existed in the area. The lake was filled by meltwater sands and varved clay in the Late Weichselian, and by gyttja in the Early Holocene — locally

Table 1. Description of selected input parameters for the model system WASMOD. Unit: SLD = soil layer depth in cm; Data type: d = dynamic; f = fixed; S = dynamic state variable; Data source: M = measured; SPD = Soil profile description; PTF = pedotransferfunction; IC = Initial conditions; O = observed; L = literature value; DSM = Digital Soil Map; DEM = Digital Elevation model; DLM = Digital land use map; VM = Vegetation map.

Input data	Data source			
	Unit	Type	Plot	Mesoscale
Soil physics				
organic matter	(%)	d	M; SPD; PTF	SPD; PTF; DSM
clay	(%)	f	M; SPD; PTF	SPD; PTF; DSM
loam	(%)	f	M; SPD; PTF	SPD; PTF; DSM
bulk density	(g cm^{-3})	f	M; SPD; PTF	SPD; PTF; DSM
conductivity	(cm d^{-1})	f	M; SPD; PTF	SPD; PTF; DSM
soil water retention (0; 1.8; 2.5; 3.5; 4.2)	(%)	d	M; SPD; PTF	SPD; PTF; DSM
moisture content	(%)	S	M for IC	PR for IC
Soil chemistry				
pH		f	M for IC	PTF
ammonia	(kg N ha SLD)	S	M for IC	PR for IC
nitrat	(kg N ha SLD)	S	M for IC	PR for IC
organic nitrogen	(kg N ha SLD)	S	M for IC	PR for IC
soil organic matter	(kg N ha SLD)	S	M for IC; PTF	PR for IC; PTF
soil microbial biomass	(kg N ha SLD)	S	M for IC; PTF	PR for IC; PTF
added organic matter	(kg N ha SLD)	S	M for IC; PTF	PR for IC; PTF
Hydrology				
surface elevation	(m a. sl)	f	M	DEM
distance to river network	(m)	f	M	DEM; RN
elevation of river	(m a. sl)	f	M	DEM; RN
drainage depth	(cm)	f	M	DEM; LUM
slope	(%)	f	M	DEM
neighbouring polygone	code	f	–	DEM
Land use and vegetation				
land use type	code	–	O	DLM; VM
leaf area index	(–)	d	M; L	
rooting depth	(cm)	d	M; L	
max N content in biomass	(kg N t)	f	M; L	
harvest type	code	–	O	O; DLM
fertilization type	code	–	O	O; DLM
fertilization amount	(kg N ha)	d	O	O; DLM
nitrogen content biomass	(kg N ha)	S	M; L	
Climate				
precipitation	(mm d^{-1})	d	M	
temperature (Tmax; Tmin)	(°C d^{-1})	d	M	
solar radiation	(J cm^{-2})	d	C	

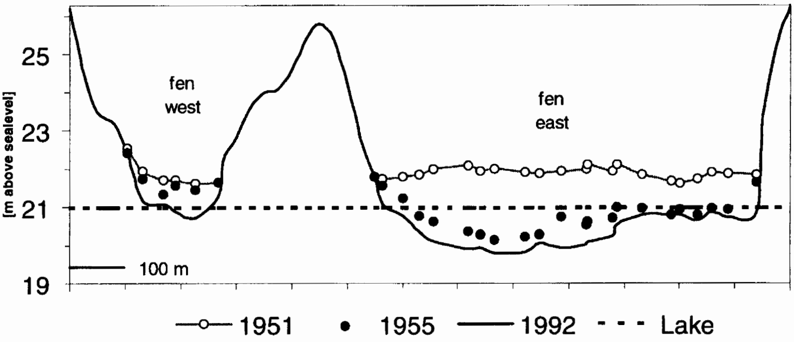

Fig. 2. Elevation of the peat surface in 1951, 1955 and 1992 in the Pohnsdorfer Stauung; Data source: 1951 and 1955: Moorversuchsstation Bremen, unpublished report; 1992: Ingenieurbüro Heidel Flintbek, unpublished report.

more than 7 m, and from the Atlantic on with a 1 to 4 m thick peat layer. The upper peat consists of highly humified *Alnus* peat, followed by a small layer of *Phragmites* peat (Weerts 1997). At the surface a more than 1 m thick layer of medium humified sedge peat and locally less humified *Sphagnum* peat layer indicates a successional shift from eutrophic to mesotrophic conditions.

Land use history

The minerotrophic fen was cultivated for agricultural purposes in 1953 by poldering the area with banks on both sites of the river Neuwührener Au and by building a pumping station, that lowered the water level in the fen by approx. 1.5 to 2 m compared to the natural hydrological situation (Fig. 2). Before 1953, only a small part of the Pohnsdorfer Stauung was drained by ditches and used as a wet meadow. Immediately after the establishment of the pumping station, a subsidence of the peat surface was measured which amounts locally up to 1.5 m (Segeberg & Eggelsmann 1953). The immediate response with high subsidence rates indicates formerly undrained hydrological conditions in most parts of the fen (Eggelsmann 1990).

From the 1950's onwards, the peat soils were used as intensive meadows and pastures with high fertilizer application. The application of CaO increased the pH from 5 to 6.5 in the upper peat layer. These agricultural practices led to a continuous peat loss and lowering of the soil surface. In the 1990's, the farmers lost interest in this peatland due to increasing drainage cost caused by continuous subsidence. They sold the area to a private nature conservation foundation, the 'Kurt-und-Erika-Schrobach-Stiftung' in Raisdorf, Kiel. The foundation established a restoration programme, including a stepwise rewetting of the peatland through an increase of the insertion level of the pumping station and by blocking drainage ditches. Presently, half of the minerotrophic peatsoils are used extensively without fertilization as meadows or pastures depending on the water levels. Only at the peatland margins, do intensive land use types occur. About one third of the peatland, mainly the central eastern part, is covered by *Phalaris*-, *Phragmites*- or sedge-reeds.

Data collection and pre-processing

In the area 'Pohnsdorfer Stauung' geology, soil, vegetation, hydrology and land use were studied in the field and stored in a database of a GIS system (Trepel 2000). For the elevation a digital elevation model with a 25 m resolution was used. For calibration of the model, the soil properties were determined in the field and compared with literature values from northern Germany (Trepel 2000). Climate data (daily measurements for precipitation, maximum-, minimum-temperature, humidity and calculated solar radiation) were measured at the nearest weather station in Ruhwinkel 15 km southeast of the Pohnsdorfer Stauung over a period of nine years from October 1988 to September 1997.

Denitrification measurements

In March and July 1998, in-situ denitrification rates were measured with an acetylene inhibition method designed for sediment studies with overlying water according to Davidsson and Leonardson (1998) at two sites, a wet and abandoned *Caricion elatae* and a slightly drained and grazed *Lolio-Potentillion.* At each site, 30 samples were randomly collected along two 50m transects. Ten samples were immediately frozen to investigate the background concentration of N_2O in the soils. Acetylene was added to the other twenty soil samples with a syringe. The samples were then incubated for 4 hours at in-situ temperature, followed by rapid freezing. Nitrous oxide concentrations in the samples were measured in the laboratory using a gas chromatograph (Varian 3300) equipped with an electron capture detector (310°C) and 2.5 m Porapak Q column (50°C).

RESULTS

Effect of land use on the nitrogen balance

Table 2 shows the simulated input and output fluxes in the nitrogen balance for different land use and vegetation types on minerotrophic peatsoils in the peatland Pohnsdorfer Stauung. The *Molinio-Arrhenatheretea* frame community (according to Schrautzer & Wiebe 1993) occurs frequently on medium deep drained peatsoils which are intensively used as meadows. In the simulation, this land use type covers with 10 polygons only an area of approximately 4 ha of peatland. The stand is mown three times a year. Nitrogen input consists of an atmospheric deposition of about 20 kg N ha^{-1} a^{-1} and 160 kg ha^{-1} a^{-1} fertilization. During simulation period, the mean annual mineralization rates amounts up to 199 ± 64 kg ha^{-1} a^{-1}. The most important output pathway is harvest with 156 ± 32 kg ha^{-1} a^{-1}, followed by denitrification with 56 ± 31 kg ha^{-1} a^{-1} and nitrogen leaching with 20 ± 19 kg ha^{-1} a^{-1}. Nitrogen losses via volatilisation are of minor importance in the nitrogen balances of the simulated system. The total annual mean nitrogen loss in the *Molinio-Arrhenatheretea* frame community totalled up to 236 kg ha^{-1} a^{-1}, with an annual input of only 180 kg ha^{-1} a^{-1} the nitrogen balance is negative with a deficit of about – 56 kg ha^{-1} a^{-1}. Mineralization is considered as an internal process and therefore not included in the nitrogen budget. At the two other agricultural land use types, the nitrogen balance is also negative. The unfertilized *Calthion* type has an annual nitrogen deficit of 33 kg ha^{-1} a^{-1}. This vegetation type occurs mostly on peat sites with high groundwater level and is mown only once in late summer. The high groundwater level results in a decrease in the annual mineralization rate. The vegetation type *Lolio-Potentillion* occurs frequently on grazed peat soils. In the simulation, the nitrogen budget is with a deficit of 20 kg ha^{-1} a^{-1} negative.

The nitrogen budgets of all agricultural sites show a deficit between nitrogen input and output

Table 2. Simulated nitrogen budget for different land use/vegetation types on minerotrophic peatsoils in the Pohnsdorfer Stauung; all values in (kg N ha^{-1} a^{-1}).

	Vegetation type				
	MA-frame-community	Calthion	Lolio-Potentillion	Caricion elatae	Lolio-Potentillion
Land use	mown 3 ×	mown 1 ×	grazed	abandoned	abandoned
Area (ha)	4	25.5	12.7	11.1	4.2
Number of polygons	10	59	26	16	7
Atmospheric deposition	20	20	20	20	20
Fertilization	160	–	60	–	–
Mineralization (intern)	199 ± 64	89 ± 60	110 ± 60	41 ± 45	134 ± 73
Harvest	156 ± 32	24 ± 17	50 ± 18	0	0
Nitrogen leaching	20 ± 19	5 ± 6	10 ± 11	1 ± 3	6 ± 9
Denitrification	56 ± 31	24 ± 19	37 ± 21	17 ± 14	34 ± 33
Volatilization	3.9 ± 1.7	0.7 ± 0.4	3.1 ± 1.8	0.4 ± 0.3	0.9 ± 0.4
Σ output	236	53	100	18	42
Saldo	– 56 ± 42	– 33 ± 30	– 20 ± 30	2 ± 16	– 22 ± 39

from the system. Their soil organic nitrogen pool is continuously reduced by denitrification following mineralization during the simulation. These systems act as a nitrogen source in the landscape. The nitrogen budget of the two abandoned vegetation types are not affected by land use. Only the nitrogen budget of the *Caricion elatae* type is slightly increased with an annual accumulation of 2 kg N ha^{-1} a^{-1}. The nitrogen budget of the formerly grazed *Lolio-Potentillion* is still negative with a mean annual deficit of 22 kg N ha^{-1} a^{-1} due to a lower groundwater table.

Spatio-temporal variation of the simulated biochemical processes

The simulated values for biochemical processes are highly variable caused by stochastic climate data for temporal variation as well as spatial heterogeneity of relief features and soil properties. The weather conditions during the nine year simulation period are extremely variable with e.g. very wet seasons (summer 1990 and summer 1994) or an abnormal drought ranging from summer 1995 to autumn 1997 (Trepel 2000). During the drought period, water and nitrogen leaching rates decreased down to zero while mineralization and denitrification increased (Trepel 1999). The assessment of the environmental impact of different land use types has to take both spatial and temporal variation into account. The GIS-based dynamic modelling approach is a tool to analyse such variation, which is of course limited by the quality of the simulation results depending on the precision of the input data as well as the model parameterisation in general (see discussion). As an example, the mean annual denitrification at the 59 *Calthion* stands in the nine year simulation period is 24 ± 19 kg ha^{-1} a^{-1}. The mean annual denitrification has a spatial variation ranging from 16.5 kg N ha^{-1} a^{-1} for the polygon with lowest up to 32.5 kg N ha^{-1} a^{-1} for the polygon with highest mean annual denitrification. The single *Calthion* stand with the lowest mean annual denitrification rate still has a high temporal variation ranging from 8.4 kg N ha^{-1} a^{-1} in 1995 to 31.7 kg N ha^{-1} a^{-1} in 1993. These results agree with measurements of nitrous oxide emissions from peat soils under grassland with different fertilization and groundwater level (Velthof et al. 1996). The measurements had a high temporal and spatial variation due to weather conditions, fertilization input and water table depth, but the sites differed also in their seasonal dynamic.

Denitrification as a main output pathway

In the simulation, denitrification is next to harvest the most important quantitative output pathway in the nitrogen budget in agricultural vegetation types as well as in abandoned or seminatural vegetation types. The annual denitrification rate is correlated to the nitrogen input, nitrification and groundwater table depth ($r = 0.42; 0.31; 0.18; p < 0.000$). This hypothesis was tested in an experiment, where denitrification was measured at two plots differing in water table depth and vegetation twice in March and July 1998.

The measured denitrification rates between the two sites are mainly influenced by drainage depth and soil moisture content (Table 3). The measured values have the same range as the simulated ones, excluding March at the *Lolio-Potentillion* site. The soil properties of the seminatural *Caricion elatae* site are only slightly affected by secondary pedogenesis due to the low drainage depth. Denitrification rates are low with values < 0.3 kg N ha^{-1} month^{-1} low. The denitrification rates at the drained and grazed *Lolio-Potentillion* site are, with values between 3.7–12 kg ha^{-1} month^{-1}, more than ten times higher. The anaerobic microbiological process denitrification is generally controlled by nitrate and carbon content in the soil. It is also affected by pH, temperature and the carbon quality e.g. different botanical composition of peat type. In organic soils, denitrification is limited in general by the nitrate concentration (Groffman et al. 1988, Verhoeven & Meuleman 1999). In our study, the denitrification is limited by the nitrification rate in the upper, better aerated, soil layer. Due to the poldering of the peatland, no nitrate inflow with the river water occurs. When nitrate is transported from the aerobic soil layer into the anaerobic layer, it can be denitrified. Because of this interaction between nitrification and denitrification, nitrogen leaching from peat soils with a predominantly vertical water movement is low. Both, measurements and simulation results

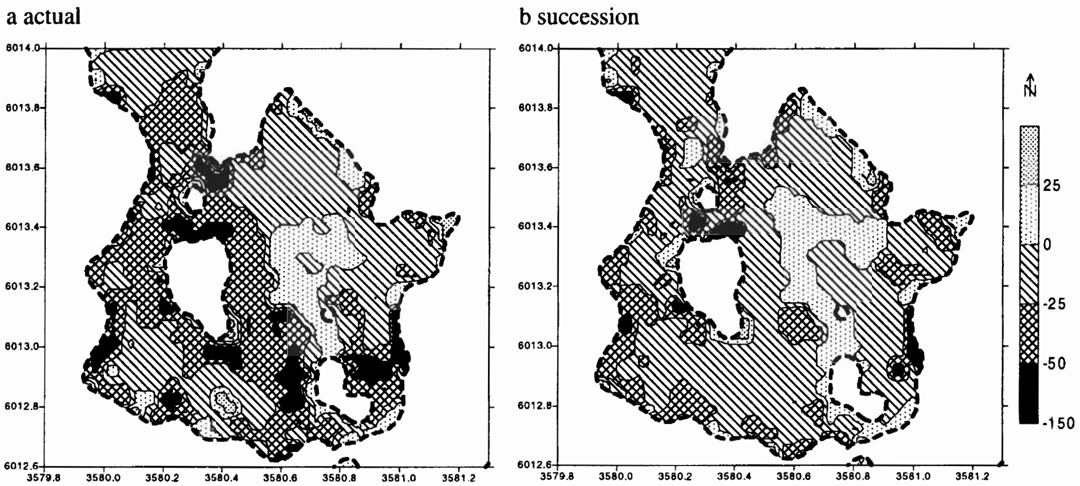

Fig. 3. Simulated nitrogen budget for minerotrophic peatsoils of the Pohnsdorfer Stauung; a = actual hydrological and land use conditions; b = succesion and natural (rewetted) hydrological conditions. Mean annual nitrogen accumulation or deficit in (kg N ha^{-1} a^{-1}) for the simulation period: October 1988 to September 1997.

indicate that nitrogen loss and therefore peat loss is mainly controlled by the water level.

Spatial pattern of the nitrogen balance

The nitrogen budget for the vegetation types is affected by land use type, fertilizer input and drainage depth. These factors have a high spatial variability in the field. The linkage of the nutrient model with a Geographic Information System takes the spatial variability into account. Fig. 3 shows the simulated nitrogen budget for the minerotrophic peatsoils in the Pohnsdorfer Stauung under two different land use scenarios. The 'actual' scenario (Fig. 3a) represents the pre-

Table 3. Measured (M) and simulated (S) denitrification rates at two plots in the Pohnsdorfer Stauung. * = denitrification below detection limit. Soil properties are for the upper soil layer (0–20 cm depth).

	Vegetation type			
	Lolio-Potentillion		Caricion elatae	
Peat type	humified		sedge peat	
Humification degree	H 10		H 4–6	
Drainage depth (cm)	– 30		– 10	
pH	5.0–6.0		4.5–5.5	
Organic carbon content (%)	35		41	
Bulk density (g cm^{-3})	0.30		0.17	
	March	July	March	July
Floodwater nitrate (mg N l^{-1})	–	–	0.03	0.06
Moisture (%)	84	94	100	100
Water/Soil temperature (°C)	8	15	4	18
Denitrification M (kg N ha^{-1} $month^{-1}$)	12.0	3.9	0.0*	0.2
Denitrification S (kg N ha^{-1} $month^{-1}$)	3.7	3.9	0.3	0.2

sent land use pattern and hydrological conditions, which are influenced by the pumping station. For the 'succession' scenario (Fig. 3b), the water level was changed to its natural, anthropogenic unaffected level resulting in flooding of large areas. Consequently, land use type was changed form formerly several agricultural and semi-natural vegetation types into only *Phragmites* reeds on all minerotrophic peatsoils. The nitrogen budget is calculated as the difference between nitrogen input and output. The dotted areas indicate locations in the peatland with a nitrogen accumulation.

Under actual conditions, accumulation areas cover only small parts in the eastern, central area of the peatland where actual water levels are due to high subsidence rates almost above soil surface. The shaded areas have a negative nitrogen budget in the simulation. They cover most of the peatland. Under present land use and hydrological conditions, the deficit in the nitrogen budget is higher in the western part of the peatland where deeper drainage levels allow an extensive land use. The central eastern part of the peatland is abandoned. Here, the deficit amounts only up to 25 kg N ha^{-1} a^{-1}.

Effect of land use changes on the nitrogen budget

In the simulation, it is possible to predict the effect of land use and hydrological changes on the water and nitrogen budget. Fig. 3b shows the simulated mean annual nitrogen budget for the succession scenario. The changes resulted in a slight increase of the area with a positive nitrogen budget in the eastern part of the peatland. In most parts of the area, rewetting and land use change reduced only the nitrogen deficit compared to the actual situation. According to the simulation results, it seems to be difficult to establish new accumulating conditions in all parts of the area. The spatial variability in the nitrogen budget is caused by the relief heterogeneity of the area and a lack of water during the summer months. At the peatland margins, the higher evapotranspiration rates of the newly established *Phragmites* reed, compared to the former vegetation type, reduce water levels and cause mineralization.

DISCUSSION

The knowledge and assessment of effects of land use management on the source-sink relationship requires a holistic understanding of the interactions between climate, geomorphology, hydrology, soil, vegetation, fauna and human activities on different spatiotemporal scales (Groffman et al. 1988, Grootjans et al. 1996). The unique hydrological character of mires and peatlands as landscape entities demands individual solutions for the development of future management programmes. The presented simulation approach uses a dynamic water and nitrogen model linked to a Geographical Information System for the quantification of biochemical processes. This tool allows a cost-efficient analysis of the individual abiotic and biotic conditions in the peatland which takes the spatial heterogeneity and temporal dynamics into account by integrating data sources from different spatiotemporal scales (Reiche 1994). Nevertheless, the quality of the simulation results depends on the accuracy of the required input data. The data for running a complex dynamic nitrogen model on a subcatchment scale can not be measured. They are obtained by evaluating available or 'easy to get' spatial data sources. In the DILAMO approach, the digital elevation model is the data set with the highest spatial resolution which gives uniqueness to all spatial units by parameter elevation, slope and distance to river network. The information about soil properties, vegetation and land use is based on soil profile descriptions, vegetation and land use maps and can not describe the specific properties of each spatial simulation unit nor the small scale variation. The soil physical and chemical input data are translated automatically from the soil profile descriptions in combination with land cover information (Reiche et al. 1999). The pedotransfer functions for soil physical data are based on measurements relating soil substrate with their specific properties (e.g. AG Boden 1994). The soil chemical input data require information about different, difficult to measure carbon and nitrogen pools. The conceptual distinction between slow and fast decay rates for the carbon pools causes problems in the partitioning of the input data at initial conditions which is sensitive for the simulated carbon and nitrogen budgets (Jensen et al. 1996). These difficulties with the input data are limitations for the application of the model on a mesoscale, as the simulated biochemical processes can not be validated with measurements. The model WASMOD has been previously validated for different agricultural and semi-natural ecosystems on both mineral and peatsoils at the site scale (Reiche 1994, Schimming et al. 1995, Trepel 2000). The simulation results from a wet meadow on a base rich minerotrophic peat soil at the Belau Lake correspond well with measured moisture, nitrate and ammonia concentrations over a five year period (Trepel 2000). The simulated output pathways in the simulation were in the same order as calculations based on measurements (Wetzel et al. 1996). Assuming, that the model WASMOD is validated for water and nitrogen transformation at a plot scale, it can be applied at a mesoscale.

In the presented case study, the standard error of the biochemical processes grouped to vegetation/land use types is an indicator for their spatiotemporal variability. According to the simulation results, the assessment of land use types concerning their environmental impact, e.g. nitrogen leaching, is always related with a high uncertainty, which is often neglected by environmental authorities. Lysimeter experiments identified fertilizer input as a regulating factor for nitrogen leaching from peat soils, while climatic variation was not considered (Ross et al. 1995). The visualisation of e.g. the nitrogen budget in a given area for different land use scenarios is a useful tool for decision makers to study the effect of different management options before they are realised. In this case study, the actual land use and hydrology of the Pohnsdorfer Stauung can not be considered as sustainable on the basis of the RAMSAR definition. The present agricultural land use types require water level regulation by a pumping station to allow mowing or grazing during the summer months which results in ongoing subsidence and nitrogen losses via several biochemical pathways. The environmental impact from peatlands is often quantified only very roughly. Schopp-Guth (1999) made a rough prediction of carbon and nitrogen mobilisation from peatlands all over Germany by using bulk density, carbon and nitrogen concentration and a mean annual subsidence rate of 0.4 cm without any spatial variation. Such figures are only useful to get the attention of environmental authorities. An effective environmental planning aiming to restore the natural functions of landscapes requires indepth knowledge of the spatial properties and variation to develop future land use management. The presented simulation approach is a tool to quantify biochemical processes with a high spatiotemporal resolution.

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