

Development and application of a semi-quantitative decision support system to predict long-term changes of peatland functions

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1 Introduction

In Europe, about 52% of the former mire area has been lost due to human exploitation (JOOSTEN & CLARKE 2002). In most western European countries, mire loss is greater than 90% (e.g. Poland, Great Britain), in some greater than 99% (e.g. Denmark, Germany, The Netherlands). Today, peatlands are covering approximately 520 000 km² of Europe, which is 83% of the former mire area.

The current agricultural use of peatlands is connected with several environmental problems. Drainage of peatlands results in soil subsidence and physical soil properties are changed irreversibly. Furthermore, drainage for agriculture and forestry causes increased emissions of greenhouse gases, increased discharge of nutrients into surface waters, and a reduction of biodiversity (JOOSTEN & CLARKE 2002, TREPEL *et al.* 2000, SCHRAUTZER & JENSEN 1999, AUGUSTIN *et al.* 1998, MARTIKAINEN *et al.* 1995).

The awareness of those problems is increasing today, which is reflected in several international conventions. The main driving force for the wise use of peatlands on an international level are the Guidelines for Global Action on Peatlands of the Ramsar Convention on Wetlands (RAMSAR CONVENTION SECRETARIAT 2004). In several European countries and regions, action plans for peatlands have been developed: Central Europe (BRAGG & LINDSAY 2003), The Netherlands (SCHOUWENAARS 2003), Russia (WETLAND INTERNATIONAL RUSSIA PROGRAMME 2003), Schleswig-Holstein/ Germany (TREPEL 2007, 2003), and Mecklenburg-Vorpommern/ Germany (LENSCHOW & THIEL 2000). More, peatlands play a significant role in other international conventions, such as the Convention of Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC).

The present study is part of the European project EUROPEAT, funded by the European Commission's 5th framework programme to handle problems connected with agricultural peatland use. The full title of the project is "Tools and scenarios for sustainable management of European peat soils to protect associated landscapes and natural areas in relation to agricultural production".

Experimental studies usually only cover short time periods. Additionally, process-based deterministic models have limits in representing the complexity of interactions. Thus, it is essential to provide tools for the evaluation of long-term changes of peatland functions in order to develop sustainable land use strategies in Europe. International conventions (Ramsar, Global Action on Peatlands) and the Millennium Ecosystem Assessment (MA 2005a) adopted the multifunctional approach (concept of ecosystem functions and ecosystem services) to evaluate sustainable development and the wise use of ecosystems. The present study is based on the concept of ecosystem functions which has been included in the guidelines for the peatlands wise use and management (JOOSTEN & CLARKE 2002).

The aim of this thesis is the development of a semi-quantitative decision support system called Peatland Management Decision Support System (PMDSS) to predict long-term changes of peatland functions. PMDSS is designed to support scientists, water boards, and environmental agencies in decision making processes for long-term management of peatlands. Application sites are minerotrophic peatlands in Europe used for agriculture, forestry, nature conservation, and abandoned land.

1 Introduction

The objectives of PMDSS are as follows:

- Definition of realistic management targets for peatlands
- Demonstration of long-term changes and interactions of peatland functions
- Support of sustainable use, conservation, and restoration of peatlands

PMDSS is implemented as an one-dimensional mathematical computer model in the spreadsheet programme Excel. As a semi-quantitative model, it includes qualitative and quantitative knowledge (BERLEANT & KUIPERS 1997). This tool is supposed to support the understanding and the prediction of long-term processes in peatland ecosystems in Europe. The amount of input parameters is reduced to parameters which are easily collectable within a few days and with low costs. These parameters reflect different peatland management scenarios, including different land use types and water management options. The model results give rough estimates and development trends of peatland functions.

The model is based on selected indicators (e.g. nitrogen discharge, Global Warming Potential) of the following peatland functions: production function, carrier function, regulation function, and informational function. The indicators represent the main problems of peatland use and are transferable into PMDSS. The spatial resolution is set to site scale. A site is defined as an area with homogeneously distributed input parameters (e.g. land use category, vegetation type, and depth to mean summer water table). PMDSS operates with annual time steps for a time span of 100 years. Vegetation development is calculated for 50 years. Within the chosen time scale, the effects of long-term processes - especially subsidence - are visible and the prediction of the indicators is reasonable.

This thesis includes two main parts: (1) the development of PMDSS and (2) its application to different case studies. The main research questions to be answered in the context of the development of the model are:

- What is currently known about long-term changes of peatland ecosystems?
- Which parameters are useful indicators of peatland functions?
- Which equations and rules well represent the behaviour of peatland ecosystems?
- How should the input interface and result presentation be designed so that PMDSS is user-friendly and understandable?

For the application of PMDSS, the following main research questions need to be answered:

- To which European peatland sites is PMDSS applicable?
- Which management issues can be analyzed with PMDSS?
- Can PMDSS be applied to support sustainable use, conservation and restoration of peatlands?

This study is structured as follows. Chapter 2 briefly reports the problems of the current peatland use.

Material and methods used for the development and application of PMDSS are described in chapter 3. The embedding of this study within the EUROPEAT project is explained in chapter 3.1. The concept of ecosystem functions is briefly introduced in chapter 3.2 and chapter 3.3 gives an overview of the modelling procedure.

Chapter 4 describes the development of PMDSS in detail: the boundary conditions of the model (chapter 4.1), the derivation of indicators (chapter 4.2) and the state of knowledge, model rules and equations in PMDSS and model output (chapter 4.3).

Chapter 5 documents all input and result parameters and worksheets which are required to apply PMDSS to the case studies.

In chapter 6, the application of PMDSS to three case studies is described and discussed. In the first case study, PMDSS is applied to a peatland site in the Eider Valley, Germany (chapter 6.1). The second case study describes the application to the peatland Mötjerpolder, Germany (chapter 6.2). In the third case study, PMDSS is applied to several sites in EUROPEAT partner countries (chapter 6.3).

In the discussion and conclusion (chapter 7), methodological and application issues of PMDSS (chapter 7.1 and 7.2 respectively) are discussed and the possible use and contribution of the model for the management of peatlands are derived. An outlook for the application and improvement of PMDSS concludes this chapter (chapter 7.3).

2 Peatland use and connected problems in Europe

In Europe, only half of the original **peatland** area is still in a largely pristine state (JOOSTEN & CLARKE 2002). The total mire area in Europe is reduced mainly due to drainage and other water management activities. In most western European countries (e.g. Denmark, Germany, The Netherlands, Great Britain), **mire loss** is greater than 90% (JOOSTEN & CLARKE 2002). In these countries, undisturbed mires are nearly extinct or belong to the most threatened ecosystem complexes (NIXON *et al.* 2000). In the countries of the project partners of the EUROPEAT consortium the mire loss varies between 21% and 99% (table 2.1). Definitions for peatland and mire as used in this thesis are given in the Glossary (Appendix A).

Drainage of peatlands results in **subsidence** (SCHOTHORST 1977). To obtain a stable water level, more effort has to be put into drainage. With rising drainage costs, agricultural land use is not profitable any more and retrieved (TREPEL 2003, SCHOUWENAARS 2002, HELLEGERS 2001). On coastal peatlands, the effect of sea level rise is adding to the problems caused by subsidence (VERHOEVEN 2002). In this case, the surface is decreasing even more (relative to the sea level), leading to higher pumping costs. Usually, subsidence is a long-term process of which land owners are not aware.

As many peatlands (especially riparian peatlands) are situated in river lowlands, they have a potential for **flood** storage or damping the flood wave (HESS *et al.* 2003, HOHENSINNER *et al.* 2003). To increase the

Table 2.1: Estimated peatland (peat depth > 30 cm, organic content > 30%) and mire area of European countries with an original peatland area greater or equal to 10 000 km² (JOOSTEN & CLARKE 2002).

Country	Original peatland area [km ²]	2002 peatland area [km ²]	2002 mire area [km ²]	2002 mire / original peatland area [%]
Belarus	29 390	23 500	11 412	39
Denmark	10 000	1 400	50	1
Estonia	11 000	10 000	3 000	27
Finland	96 000	85 000	32 000	33
Germany ^a	16 250	13 000	100	1
Great Britain ^a	19 000	17 500	1 000	5
Ireland	12 000	11 500	2 100	18
Netherlands ^a	15 000	2 350	150	1
Norway ^a	30 000	28 000	22 000	73
Poland ^a	20 000	12 500	2 000	10
Russia European part	243 000	213 000	150 000	62
Sweden ^a	70 000	66 000	55 000	79
Ukraine	11 000	8 000	5 800	53
Europe	617 492	514 882	294 702	48

^acountries of the EUROPEAT project partners

Table 2.2: Problems of peatland use and their weighting (+: low, ++: middle, +++: high weighting) as mentioned from the project partners of EUROPEAT at the first meeting in November 2002 in Wageningen.

Country	Mentioned problems 2002									
	Subsidence	Water quality	Sustainable agriculture	Habitats	Climate change	Recreation	Flood storage	Archaeology	Drainage	Peat extraction
Germany	+	+++	+	++						
Great Britain	++	++	+	+		+	+	+		+
Netherlands	+++		+++	+						
Norway	+		++						+	
Poland		+++	++	+						
Sweden			+		+++					

agricultural use of peatlands, they are often protected against floods by dykes. This contributes to the overall loss of flooding area and causes higher floods in more sensitive regions like settled areas.

Peatlands have a high potential for the improvement of **surface water quality** (VERHOEVEN *et al.* 2006). Due to intensive agricultural land use in the upstream catchment area, nutrient inflow into a peatland can be very high. Transformation and immobilization processes in peatlands may lead to much lower nutrient concentrations in the water outflow than in the water inflow. Drained peatlands often do not fulfil the retention function. They may even act as a source of nutrients due to additional nutrient sources from fertilizer input and mineralization of the peat. High nutrient discharge rates of peatlands lead to eutrophication of rivers and lakes.

Peatlands play an important role in the global cycle of **greenhouse gases** (BYRNE *et al.* 2004). Pristine mires are important sinks for CO₂. About one third of the total global soil carbon pool is stored in peat (POST *et al.* 1982). The mean carbon content of undisturbed peat soils can be estimated with 40% (MITSCH & GOSSELINK 2000b) and the mean nitrogen content with 0.5 - 3.5% (KOPPISCH 2001a) on a dry-weight basis. Drainage of peatlands leads to CO₂- and N₂O-emission. In general, drained peatlands have a higher Global Warming Potential than pristine mires or rewetted peatlands. Methane emissions occur mainly in pristine mires or rewetted peatlands with water levels near the surface (JOOSTEN & CLARKE 2002).

Degradation and subsidence of peat soils cause problems in the restoration of peatlands, because these changes alter the physical properties of the peat soils irreversibly (SCHRAUTZER *et al.* 2007, ILNICKI & ZEITZ 2003, BLANKENBURG *et al.* 2001).

As in other ecosystems, there is a loss of plant and animal species. In many peatlands, this is due to the exploitation and intensification of land use. Furthermore, the abandonment of marginal sites due to socio-economical reasons initiates a secondary succession which usually causes the decrease of plant **biodiversity** (WOŁEJKO 2002, SCHRAUTZER & JENSEN 1999, FOJT & HARDING 1995, ROSENTHAL 1992). These marginal sites are typically less intensively used peatlands.

The mentioned problems show that there is a need to change the current use of peatlands towards a more sustainable peatland management. Often the discussed problems are regarded separately and stakeholders are not aware of all of them. At the beginning of the EUROPEAT project in 2002, the awareness of the problems differed in the countries of the project partners (table 2.2).

3 Material and methods

3.1 EUROPEAT project of the European Union

As mentioned in chapter 1, the present work is part of the European project EUROPEAT ("Tools and scenarios for sustainable management of European peat soils to protect associated landscapes and natural areas in relation to agricultural production"), funded by the European Commission's 5th Framework Programme. The project started in September 2002 and ended in February 2006.

Main objectives of the EUROPEAT project were:

- to elucidate the processes determining the rate of subsidence, oxidation, and release of nutrients and greenhouse gases from peat soils;
- to improve the prediction of the effect of land use, water management and global climatic change on these processes;
- to quantify the effects of peatland deterioration;
- to assess the socio-economic impact of environmentally driven changes in peat soil management;
- to provide the basis for sustainable management of peat soil systems and the selection of peatlands suitable for agricultural or low intensity agricultural purposes, nature reserves, or restoration.

Scientists from six institutes of six countries participated in the project:

- ALTERRA, Green World Research, Wageningen, The Netherlands
- Ecology Centre, Christian-Albrechts-University of Kiel, Germany
- Warsaw Agricultural University, Department of Environmental Development and Land Improvement, Poland
- National Soil Resources Institute, Cranfield University, Silsoe, Great Britain
- Swedish University of Agricultural Sciences, Department of Soil Sciences, Sweden
- Jordforsk, Norwegian Centre for Soil and Environmental Research, Norway

The project consists of eight work packages (WP); the development of PMDSS occupied an own work package (WP6):

- WP1. Collection of available data on long term experiments. Selection of experiments for further investigation in WP3.
- WP2. Construction of a database with input for models and decision systems. Determination of pedotransfer functions.
- WP3. Experiments for studying processes and model parametrization, calibration, and validation.
- WP4. Experiments for studying the effect of existing and proposed management practises on trafficability, workable days, peat properties, degradation, environmental impacts, and regeneration of peat soils.

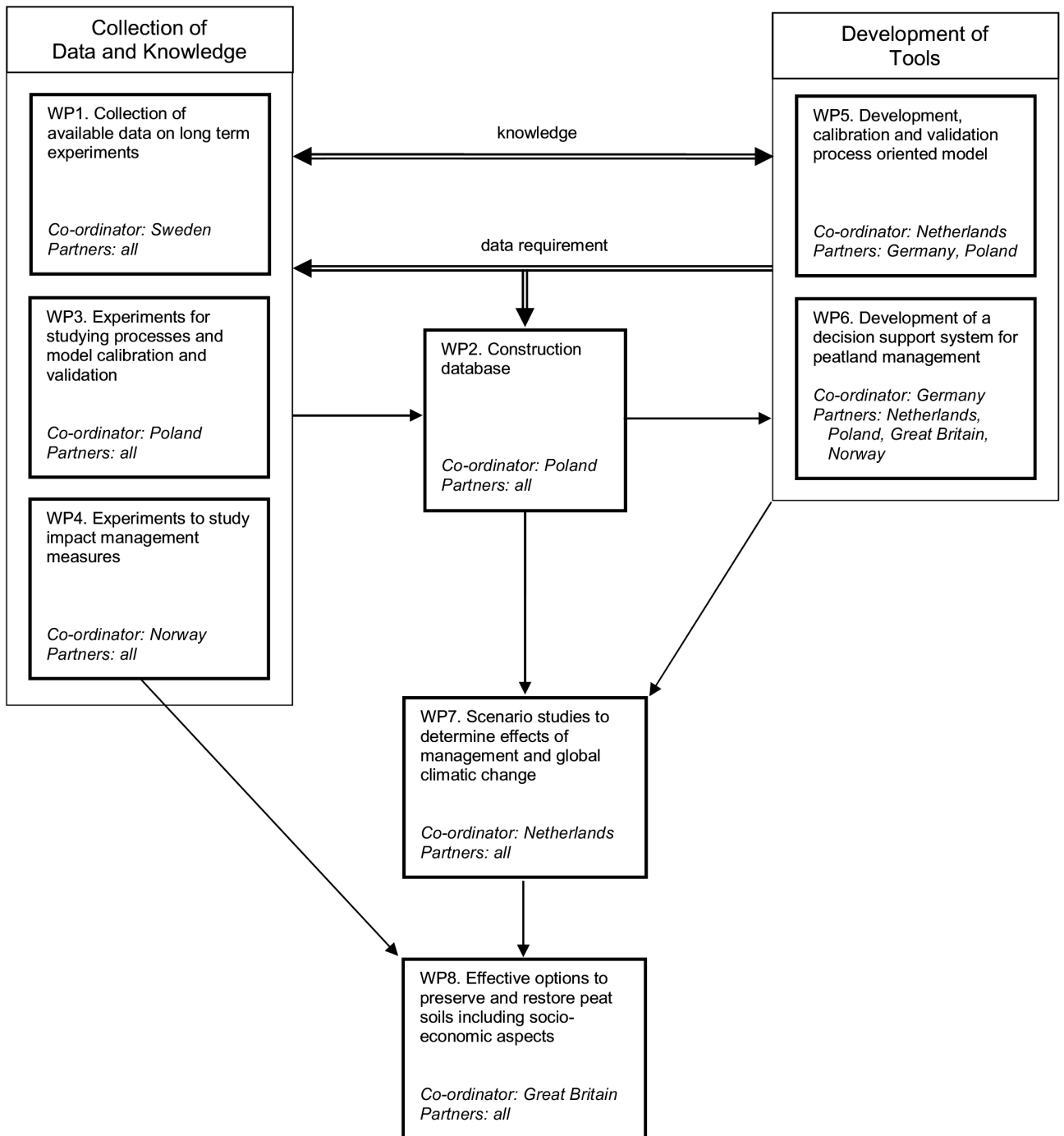


Figure 3.1: Management structure of EUROPEAT project: presentation of interrelationships between project work packages and partners involved (source: proposal of EUROPEAT project).

- WP5. Further development of an existing process oriented model (SWAP/ ANIMO) for prediction of subsidence, nutrient releases, and emission of greenhouse gases (GHGs).
- WP6. Development of a semi-quantitative decision support system for peatland management.
- WP7. Scenario studies to determine the effects of land use, water management, and global climatic change on the deterioration and restoration of peat soils and impact on GHG emissions and nutrient leaching.
- WP8. Determination of effective land use and water management to preserve and rehabilitate peat soils and minimize GHG emissions and nutrients leaching, taking socio-economic aspects into account.

The relationship between project work packages and partners involved is visualized in figure 3.1. Within WP3, each partner country selected two or more fields on peat soils to study the processes of water movement, nutrients leaching, and emission of greenhouse gases (in the following referred to as EUROPEAT sites). In Germany, the Eider valley peatland was selected as a study area for regular field measurements as well as laboratory measurements. A site description is given in chapter 6.1.2 on page 70).

The development of PMDSS is mainly based on knowledge about peatlands in northern German lowlands. Yet, data, knowledge, and feedback of the project partners contributed substantially to the development of PMDSS. For model calibration and validation, PMDSS was applied to EUROPEAT sites of Germany (chapter 6.1) as well as of three other partner countries (chapter 6.3).

3.2 Concept of ecosystem functions and indicators

In many international conventions, multifunctional approaches to evaluate ecosystem developments have been adopted (Ramsar, Global Action on Peatlands, Millennium Ecosystem Assessment). The basic concept of these multifunctional approaches is that ecosystems support the life of human beings through several functions (DE GROOT 1992). A consortium of peatland organisations, including the International Peat Society (IPS) and International Mire Conservation Group (IMCG), have included multifunctional approaches in the developed guidelines for peatlands wise use and management (JOOSTEN & CLARKE 2002). This so called "Wise Use Book" is a background document for Ramsar and is part of its Guidelines for Global Action on Peatlands (RAMSAR CONVENTION SECRETARIAT 2004).

The Ramsar convention updated the definition of wise use in 2007, which is as follows:

"Wise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development" (RAMSAR CONVENTION SECRETARIAT 2007).

The development of PMDSS is based on the multifunctional concept, adopted by JOOSTEN & CLARKE (2002). Peatlands provide beneficial functions in global, regional, and local terms to support the material and non-material life of human beings. For the use in PMDSS four main ecosystem functions are used: production function, carrier function, regulation function, and informational function.

Production functions relate to the capacity to provide resources such as water, food, and raw material for industrial use.

Carrier functions relate to the capacity to provide space and suitable subsoil for human habitation, industry, and infrastructure.

Regulation functions relate to the capacity of peatlands to regulate essential ecological processes and life support systems, contributing to the maintenance of adequate climatic, water, and soil conditions.

Table 3.1: Classification of mathematical models (after MULLIGAN & WAINWRIGHT 2004)

Mean of classification	Types of models
Conceptual type	Empirical, conceptual, physically based
Mathematical type	Deterministic, stochastic
Spatial type	Lumped, semi-distributed, distributed, GIS, 2D, 3D
Temporal type	Static, dynamic

Informational functions relate to the capacity to provide opportunities for cognitive development, including recreation, identification, education, and the existence of plants, animals, and ecosystems.

Furthermore, JOOSTEN & CLARKE (2002) account for transformation and option functions which are not taken into consideration in PMDSS. These functions refer to future aspects of all other functions, such as providing a change of preferences, character building, and providing insurance and heritage.

In the present work, the development of different ecosystem functions of peatlands will be described with indicators (chapter 4.2). An indicator is a quantifiable attribute of a physical object, process or state, with which a more complex environmental condition can be described (BAUMANN 2001, HYATT 2001). Different concepts for the derivation of indicators for the sustainable development of ecosystems are summarized in WIGGERING & MÜLLER (2004). DALE & BEYELER (2001) suggest the following criteria for selecting ecological indicators. They

- are easily measured,
- are sensitive to stresses on the system,
- respond to stress in a predictable manner,
- are anticipatory: they signify an impending change in the ecological system,
- predict changes which can be averted by management actions,
- are integrative: the full suite of indicators provides measure of coverage of the key gradients across the ecological systems,
- exhibit a known response to natural disturbances, anthropogenic stresses, and changes over time, and
- have low variability in response.

3.3 Decision support systems and modelling procedure

There is a broad variety of definitions of a **decision support system** (DSS). One commonness of many authors is that a decision support system is computer-based system which supports decision making (BURKE 2004, ENGELEN 2004, BUNNELL & BOYLAND 2003, UBBELS & VERHALLEN 2000, ADELMAN 1992).

PMDSS is a mathematical computer **model**. Many model textbooks start with the simple expression that a model is an abstraction of reality (MULLIGAN & WAINWRIGHT 2004, ODUM & ODUM 2000, JOERGENSEN 1996). The best model is always the one which is as simple as possible and as complex as needed. Mathematical models express states and rates of change with mathematical rules (MULLIGAN & WAINWRIGHT 2004). They can range from simple equations to complex software codes applying many equations and rules over time and space discretizations.

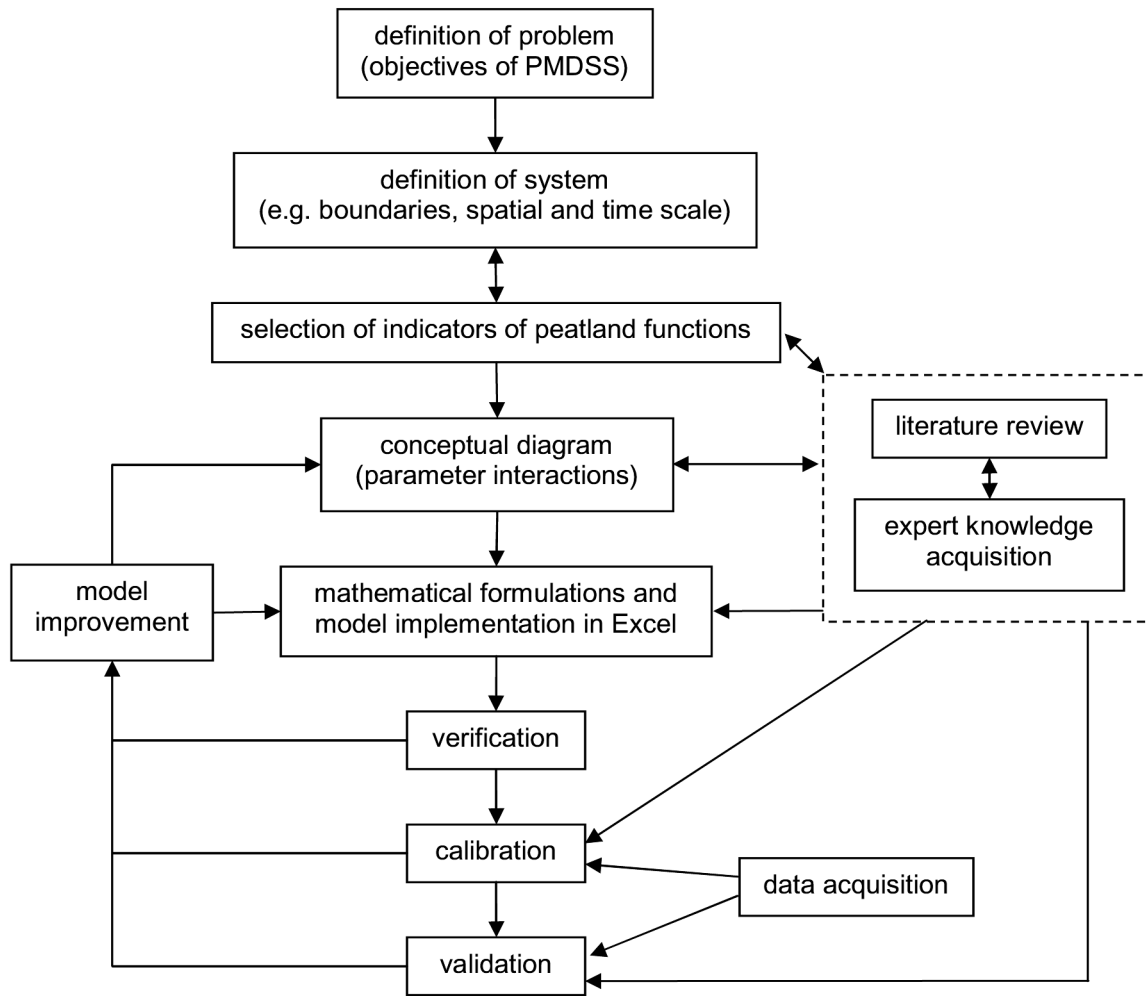


Figure 3.2: Modelling procedure as applied for the development of PMDSS (adapted from JOERGENSEN 1996).

Important is the **purpose** of a DSS. BUNNELL & BOYLAND (2003) distinguish four broad purposes, a DSS can serve:

- aid research,
- guide management,
- conveying knowledge, and
- public evaluation of tradeoffs.

The main focus of PMDSS lies on the purposes to guide management and convey knowledge. Among the criteria of a DSS to meet those purposes are the ability to help decision-makers to come to fast predictions about the systems behaviour with confidential accuracy, transparency, and the ability to illustrate connections and effects quickly. Thus, it has to provide documented and reproducible results. During the model development, gaps in the knowledge of peatland functioning became visible. Closing these gaps will be an issue for future research.

Concerning wetlands and peatlands, several DSSs have been developed (DSS-WAMOS (<http://dss-wamos.de/>), GOOSEN *et al.* 2007, JANSSEN *et al.* 2005, KOFALK *et al.* 2004, TREPEL 2004a, TREPEL & KLUGE 2004, PALLOTTINO *et al.* 2003, UBBELS & VERHALLEN 2000). Depending on the target, a DSS is one model or a set of tools. The model types used for a DSS are varying, whereas most models are a mixture of many types (table 3.1). Not a single existing system simulates the interactions between the indicators of peatland functions with a temporal dynamic approach. Thus, the decision support system PMDSS fills a gap within the already existing modelling approaches.

The tentative **modelling procedure** of PMDSS is illustrated schematically in figure 3.2. The first step is the definition of the problem which is formulated in the introduction of the thesis (see chapter 1). The definition of the system includes the specification of space, time, and subsystems under consideration (see chapter 4.1). The selected indicators of peatland functions (see chapter 4.2) are the basis for further model development and have to be relevant for the defined problem and system.

A conceptual diagram was the basis for the following mathematical formulations of processes, rules, and relations, as well as the implementation in Excel. As PMDSS needs predictive power, mainly empirically based equations are used. Qualitative and quantitative knowledge is included with equations and rules. Physically or process-oriented models are often too complex; parametrization and calibration require too much effort (MULLIGAN & WAINWRIGHT 2004).

Indicator selection and further steps in model development are based on literature reviews and expert knowledge. The State of knowledge about system behaviour, the most important factors influencing the indicator values and existing equations were derived from the literature and expert knowledge. Expert knowledge includes feedback and suggestions of colleagues, EUROPEAT project partners, the advisory board, and participants of conferences. Furthermore, some modules were developed by or in cooperation with colleagues being experts in the relevant field (vegetation module by Bettina Holsten, nitrogen module with Michael Trepel, hydrology module with Winfrid Kluge). Initially, the development of PMDSS was based on knowledge from northern Germany.

Verification is an important step after the implementation of the model in Excel. The calibration of PMDSS was carried out during the model development (see chapter 4) and with the help of the case studies of northern Germany (see chapter 6.1 and 6.2). Result values and development trends had to be in order of magnitude and in accordance with literature values, expert knowledge, and measured data. For all case studies, the validity of results is indicated (see chapter 6). Model development is an iterative process involving loops. This is illustrated with arrows in figure 3.2.

4 Development of the decision support system PMDSS

4.1 Boundary conditions

Application sites are minerotrophic peatlands in Europe used for agriculture, forestry, nature conservation, and abandoned land. The spatial resolution of the model is the site scale. A site is the area where the input parameters (mainly land use category, vegetation type and water table) are reasonably homogeneous. The site is influenced by its landscape setting such as upstream area, lateral surface water, and subterraneous catchment of the site (figure 4.1). The user of the model can choose different peatland management scenarios which include the selection of different land use types and water management options. PMDSS has to be easily understandable, so a wide range of people with different knowledge background should be able to use it. Thus, it is a semi-quantitative model realized in an easy to use spreadsheet (Excel). Rules and equations were developed from literature review, expert knowledge, and assumptions. Input data should be easily collectable within a few days, thus input data for PMDSS are minimized.

The model is focused on the change of peatland functions (production function, carrier function, regulation function and informational function) over time and the interactions between the system components (subsidence, land use, carbon, nitrogen, Global Warming Potential, vegetation, hydrology). The model is running with annual time steps and for a time span of 100 years. The vegetation development is calculated for 50 years.

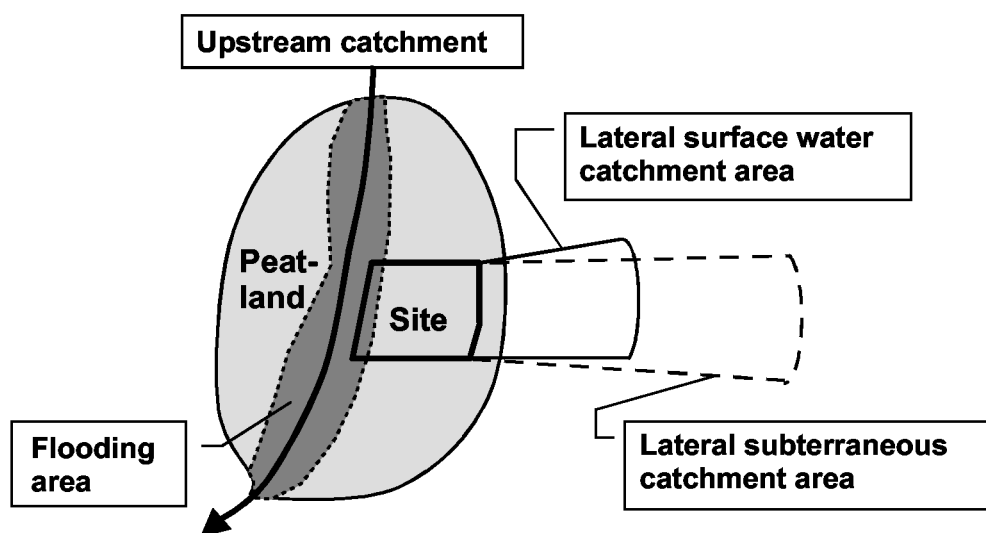


Figure 4.1: Sketch of the spatial resolution (the site scale) of PMDSS. The site is situated within a peatland and influenced by the upstream catchment and lateral surface and subterraneous catchment and might be flooded from the river.

4.2 Derivation of peatland functions and indicators

For the development of PMDSS, the four main functions of ecosystems (production function, carrier function, regulation function, informational function) are further subdivided. Indicators are selected for each function (table 4.1) in accordance to the boundary conditions described in the previous chapter.

The selection of subfunctions and their indicators is based on:

- their representation of the problems of current peatland use (chapter 2),
- their representation of sustainable peatland use,
- the possibility of their quantification (available information),
- the possibility of transferring them into the model, and
- their relevance on the site scale.

The focus of PMDSS primarily lies on agricultural land use. In addition, forestry, nature conservation, and abandoned land are included. Thus, **production and carrier function** are limited to those land use types. The harvest of plant products serves as an indicator for the production function. In terms of milk and meat production, this indicator accounts for the uptake of plants by animals. The carrier function is indicated by the land use category, where 12 different categories are distinguished (chapter 4.3.2).

The **regulation function** is subdivided into the three functions of peatlands to regulate (1) the catchment hydrology, (2) the catchment hydrochemistry, and (3) the global climate.

For the **regulation of the catchment hydrology**, the mean summer water table is selected as indicator. Peatlands are often transitional systems between terrestrial and aquatic ecosystems (MITSCH & GOSSELINK 2000b). They are transitional in terms of spatial arrangement, the amount of water they store and process, and in other ecological processes which result from the water regime. Several case studies have examined the hydrological characteristics of specific peatlands (PRICE *et al.* 2005, BULLOCK & ACREMAN 2003). Pristine peatlands significantly influence the hydrology in a catchment. They change particular components of the water cycle. Often flood flow, evapotranspiration, water outflow, groundwater recharge, and flow variability are of special interest. A systematic summary describing the hydrological function of different peatland types within the catchment in general is currently missing (BULLOCK & ACREMAN 2003). The hydrology is varying with peatland type and the site specific geohydrological situation. Drainage of peatlands changes the hydrological regulation function significantly. The water table is an important parameter

Table 4.1: Peatland functions and associated indicators.

Peatland function		Indicators	Unit
Production function	Agriculture, Forestry	Harvest of plant products	t dry matter ha ⁻¹ a ⁻¹
Carrier function		Land use category	categories 1 - 12
Regulation function	Catchment hydrology	Mean summer water table	cm below surface
	Catchment hydrochemistry	Nitrogen discharge	kg N ha ⁻¹ a ⁻¹
	Global climate	Global Warming Potential	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹
Informational function	Existence of plants, animals and ecosystems	Conservation value of plants	-

affecting the water balance. Beyond it, biological and biogeochemical processes in peatlands are largely governed by the mean summer water table which is thus needed for the simulation of most other indicators in PMDSS.

Nitrogen discharge was chosen as an indicator for the **regulation of the catchment hydrochemistry** at the site scale. Nitrogen and phosphorous are the main contributors to the nutrient input into rivers and lakes. In general, peatlands have a high potential for improvement of surface water quality via several biogeochemical processes, leading to decreased phosphorus and nitrogen concentrations at the peatland outflow (VERHOEVEN & MEULEMAN 1999).

The function **regulation of the global climate** is indicated by the Global Warming Potential (GWP). The GWP is an index to estimate the potential future effect of trace gases upon the climate system (IPCC 2001). It is calculated for the most important greenhouse gases (CO₂, CH₄, N₂O) for three different time horizons (20, 100, and 500 years). Peatlands play an important role in the exchange of greenhouse gases and thus for the global climate. In peatlands, carbon is stored in biomass, litter, and peat. CO₂ is sequestered from the atmosphere by plant photosynthesis and transformed into biomass. At high water tables, there is mainly CH₄-emission. In drained peatlands, CO₂-emission dominates. N₂O is an intermediate product of denitrification and is emitted from drained peatlands. (NYKÄNEN *et al.* 1995)

The **informational function** includes subfunctions such as history, recreation, aesthetic, symbolization, and cognition function. With the selection of the subfunction **existence of plants, animals and ecosystems**, it is assumed that the other informational functions are served then as well. This can be underlined with the expression that "informational functions are usually best performed when nature is left untouched as much as possible" (DE GROOT 1992: 129). For PMDSS, the indicator 'conservation value of plants' was selected which is an index for the coverage of threatened plant species in the simulated area. In cultural landscapes, areas with high conservation values are often connected with moderate grassland use.

4.3 Development of model rules and equations

In order to calculate indicators and intermediate results, PMDSS is divided into seven modules (subsidence, hydrology, land use, vegetation, carbon, nitrogen, Global Warming Potential) representing most important components of peatland ecosystems (figure 4.2). Abrupt changes are possible due to changes in the forcing functions land use and water management. The arrows in figure 4.2 visualize the interactions between the system components. The processes 'subsidence' and 'vegetation succession' may cause long-term changes within the peatland ecosystem.

In the following chapters, the modules of PMDSS are described. First, the state of knowledge is presented, followed by the explanation of the main equations. In order to transfer the equations into Excel, further enquiries and rules are introduced. The parameters are calculated for every year. Details of implementation can be looked up in the Excel sheets of the model itself (downloadable at <http://www.ecology.uni-kiel.de/~akniess/PMDSS>). The structure of PMDSS with the different worksheets and the input and result parameters are described in detail in chapter 5 on page 54.

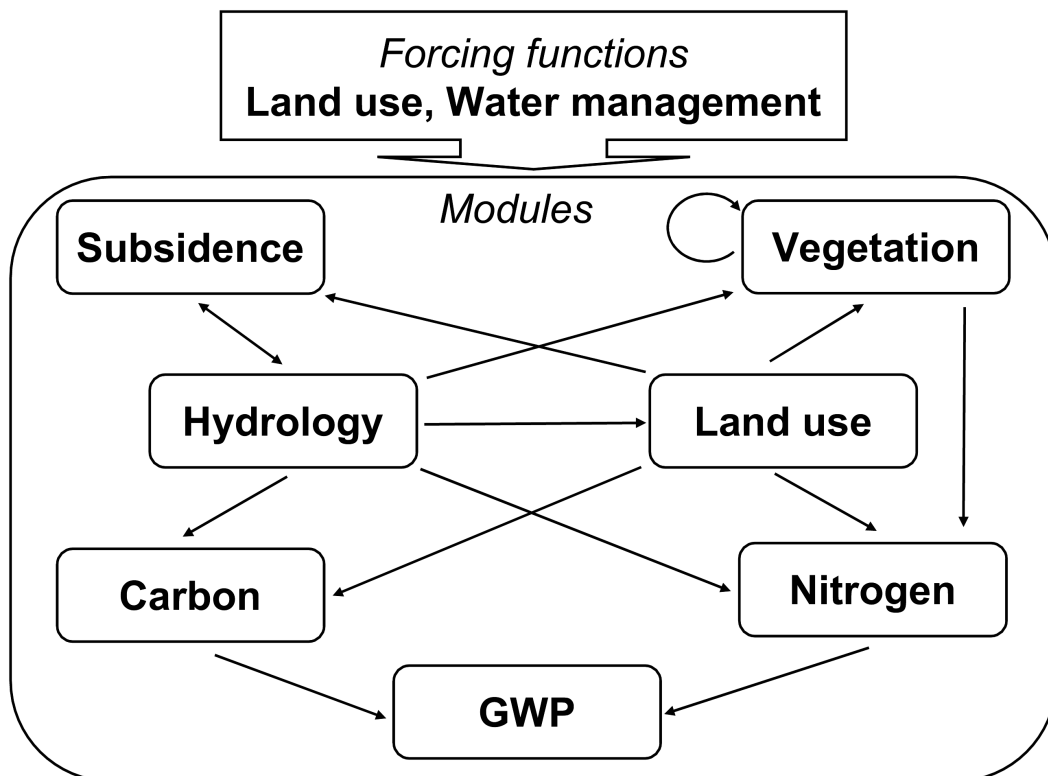


Figure 4.2: Modules and forcing functions in PMDSS (GWP = Global Warming Potential). The arrows show the interactions between the modules. Vegetation succession cause continuous change within the module.

4.3.1 Subsidence and peat growth

4.3.1.1 State of knowledge

As commonly known, oxidation, shrinkage, and compression lead to **subsidence** of the surface in drained peatlands (STEGMANN & ZEITZ 2001, SCHOTHORST 1977). The terms 'oxidation' and 'mineralization' are often used synonymously in the literature. Three components of subsidence are distinguished: (1) Oxidation: The entry of air into the soil causes oxidation of organic matter through biochemical processes. Organic material is split into substances such as carbon dioxide (CO₂), methane (CH₄), and ammonia (NH₃). (2) Shrinkage: Due to moisture withdrawal from the upper soil layers, high moisture tensions result in a decrease in volume. Shrinking and swelling are complementary processes varying with the change of soil moisture during a year. In the long run only irreversible shrinkage leads to subsidence. (3) Compression: After lowering of the groundwater level, the buoyant force is lost in the upper layers. The deeper layers, then, have to bear an increased weight, which will cause compression of the soil layers below the phreatic surface.

Shrinkage and compression have the highest contribution to subsidence in the first years after drainage, whereas oxidation is a continuous process and gets more important on long-term scale. This leads to highest subsidence rates every time after a lowering of the groundwater level. It can be assumed that the first fast subsidence process is mainly completed after approximately seven years (ILNICKI & EGGELSMANN 1977, SEGEBERG 1960). SCHOTHORST 1977 reported that six years after drainage, 65% of subsidence could be ascribed to shrinkage and oxidation of the aerobic layer and 35% to compression of the anaerobic layers. Concerning long-term subsidence, he ascribes 15% to shrinkage and 85% to oxidation. OKRUSZKO (1989) found a similar proportioning (23% and 77% respectively).

Subsidence mainly depends on drainage depth, yet also on climate, temperature, peat thickness, peat type, and bulk density (STEGMANN & ZEITZ 2001, WÖSTEN *et al.* 1997, ILNICKI 1977, EGGELSMANN 1976). More, subsidence is generally higher in minerotrophic than in ombrotrophic peatlands. EGGELSMANN (1976) showed that there is a relationship between annual subsidence at arable land use and the climate factor after LANG ($f = \text{precipitation}/\text{temperature}$)(LANG 1915).

From long-term **measurements** of soil surface at different sites, subsidence lines were plotted, showing the change over time (EGGELSMANN 1990, ILNICKI & BURGHARDT 1981, ILNICKI & EGGELSMANN 1977, STEPHENS & SPEIR 1969). In Germany subsidence rates are usually between 0.2 and 2.5 cm/ a and can get even higher than 4 cm/ a worldwide (table 4.2).

In coastal regions, mean sea level rise is adding to the problem of soil subsidence (TURNER 2004). Along the Frisian coast in the Netherlands, the rate of mean sea level rise was about 1.7 cm a⁻¹ at the end of 20th century (NIEUWENHUIS & SCHOKKING 1997).

Many different **equations** for calculating the subsidence of peat soils and peat growth have been developed in the 1960s and 1970s (ILNICKI 1977). In Europe, subsidence is often calculated by the equations of Panadiadi-Ostromecki (equation 4.1), Hallakorpi (equation 4.2), or Segeberg (equation 4.3) (SEGEBERG 1960). They calculate the short-term subsidence after first drainage or redrainage (for 5 to 7 years):

$$S = A \sqrt[3]{T_S \cdot t^2} \quad (4.1)$$

$$S = a \cdot (0.08 \cdot T_S + 0.066) \quad (4.2)$$

$$S = k \cdot tn \cdot T_S^{0.707} \quad (4.3)$$

where S = subsidence of soil surface [m], T_S = thickness of peat layers before drainage [m], A , a , k = three different factors depending on bulk density, t = depth to water table after subsidence [m] and tn = depth

Table 4.2: Subsidence rates of minerotrophic peatlands with long-term drainage under otherwise different conditions.

Area of validity (Source)	Depth to mean annual water table [cm]	Depth to mean summer water table [cm]	Further factors	Subsidence rate [cm/a]
Northeast Germany (MUNDEL 1976)	30		Peat thickness = 50 cm	0.18
	60			0.24
	90			0.31
	120			0.24
	30		Peat thickness = 150 cm	0.41
	60			0.59
	90			0.70
	120			0.69
Germany (HENNINGS & HOHMANN 2000 in RATZKE & KNICKMEYER 2002)			Intensive agricultural land use	1 - 2.5
			Extensive agricultural land use	0.3 - 0.8
Province of Friesland, The Netherlands (NIEUWENHUIS & SCHOKKING 1997)	40		Without clay cover	0.6 - 0.8
	80			1 - 1.2
	120			1.4 - 1.6
	40		With clay cover	0.2 - 0.4
	80			0.6 - 0.8
	120			1 - 1.2
Sweden (BERGLUND 1996)			Grazing lands	0.5
			Grassland used for hay	1
			Cereals	1 - 2
			Intensively cultivated crops like carrots and potatoes	2 - 3
World (EGGELSMANN 1990)		> 100	Annual temp. > 10°C, precipitation < 500 mm, arable land (root crop)	≥4
		70	Annual temp. 8°C, precipitation 700 mm, arable land (grain)	3
		< 40	Annual temp. < 6°C, precipitation > 900 mm, grassland/forest	≤2

of drains after subsidence [m]. With these formulas, subsidence can be calculated for different layers and summarized afterwards.

BLANKENBURG *et al.* (2001) give two linear equations for calculation of subsidence and peat growth, based on expert knowledge. Subsidence, mainly due to mineralization, M [mm a⁻¹] at depths to mean summer water tables greater than 10 cm and under grassland is calculated with:

$$M = 0.143 \cdot (SWT - 10) \quad (4.4)$$

SWT = mean summer water table [cm below surface]. For arable land use, mineralization rate has to be multiplied by 2. At mean summer water tables less than 10 cm below surface, peat growth PG [mm a⁻¹] is calculated with:

$$PG = -0.067 \cdot (SWT - 10) \quad (4.5)$$

MURASHKO (1969) developed an equation for compression on peat bogs after drainage, depending on depth of layer, space between canals, and time on basis of data of long-term experiments. Furthermore, regression equations have been developed for subsidence, mainly depending on water table, based on measurements (RENGER *et al.* 2002, WÖSTEN *et al.* 1997, UHDEN 1966).

RENGER *et al.* (2002) developed four regression equations for four different types of the minerotrophic peatland in northeast Germany, used for grassland. The equation accounts mainly for subsidence due to mineralization as the sites were already drained for several years, where Erd-fen is less mineralized than Mulm-fen. The equations were developed for: type a) Erd-fen with peat thickness ≥ 1 m; type b) Erd-fen with peat thickness ≤ 0.5 m; type c) Mulm-fen with peat thickness ≥ 1 m; type d) Mulm-fen with peat thickness ≤ 0.5 m. Mineralization rates go down from peatland type a to d. The regression equation for peatland type a is as follows:

$$DPT = 0.147 \cdot SWT - 0.0006 \cdot SWT^2 + 0.05 \quad (4.6)$$

where DPT = Decrease of peat thickness [mm a^{-1}] and SWT = mean summer water table [cm below surface].

In the Netherlands the **model** POXAPS was developed to calculate subsidence, focused on mineralization and irreversible shrinkage of peat in each layer per year according to SCHOTHORST (1982) (BOELS 1996).

Peat growth can be described with growth in height, lateral expansion, accumulation in dry mass or amount of carbon (RYDIN & JEGLUM 2006, KOPPISCH 2001b, CLYMO 1984). If decomposition of plant material is inhibited, peat is accumulated, usually due to anaerobic conditions at high water tables. Each year, a certain amount of material is added on top of the peat profile, where a proportion is mineralized. A small portion of all material is lost by anaerobic decay. If the addition is larger than the decay, the peatland increases in thickness. While the peatland gets older and higher, the growth rate is decreasing due to increasing decay with increasing peat thickness. Sometimes, the peatland reaches a stage where the decay equals the input. Then, it ceases to grow in thickness. It can also be assumed that peat growth starts again at rewetted peatlands (RICHERT 2001). The long-term vertical peat growth is usually lower than 1 mm per year (RYDIN & JEGLUM 2006, SUCCOW 2002, FRANZEN 1994, TOLONEN *et al.* 1992, OVENDEN 1990). BLANKENBURG *et al.* (2001) used a growth rate of 0.67 mm in equation 4.5.

The **water table** of a peatland is an important factor for subsidence and peat growth. In turn, the water table is also influenced by the factors subsidence and peat growth beside drainage type and bulk density. After first drainage or redrainage, the ditches and drains subside less than the soil surface (SEGERBERG 1960). Thus, water table relatively to mean sea level as well as the depth to water table decreases. As for long-term subsidence, mineralization of aerobic peat layer plays the major role; subsidence of ditches and drains are then very small. If a pumping station regulates the ditch water levels, they can be kept at defined levels. Furthermore, the increasing bulk density of a drained peatland influences the water table between ditches and drains. If ditches and drains are not maintained, they will lose the drainage force over time. Depth to water table may decrease and water table relatively to mean sea level may even increase.

In pristine mires, water table is near surface and usually the depth to water table stays the same while peat is growing. If a rewetted peatland is ponded, either the water table is above soil surface or some peat is separating from the ground and is swimming on the water surface.

4.3.1.2 Module description

The PMDSS subsidence module was developed on the basis of the state of knowledge (summarized in the last chapter) and will be described in the following paragraphs.

The default setting is that subsidence rate and mean summer water table are calculated in worksheet *Mod_Subs* as described in this chapter. If the parameter 'Use of Hydrology module (Input_Hydro)' was set to 1, the mean summer water table is mainly calculated in worksheets *Mod_Hydro1* and *Mod_Hydro2* (explained in chapter 4.3.7). PMDSS is also able to calculate the subsidence rate with an equation inserted by the user into worksheet *Mod_Adj* (if parameter 'Inserting new equations in Mod_Adj' was set to 1).

The calculation of the **subsidence rate** is based on a regression equation between the mean summer water table and the subsidence rate for a minerotrophic peatland in northeast Germany (equation 4.6; RENGER *et al.* 2002). For the use in PMDSS, equation 4.6 was extended with a temperature factor, a subsidence factor, and a land use factor. Thus, a plausible curve progression is used and made applicable to other sites. Additionally, the mean summer water table is reduced by mineral layers above the mean summer water table and below the peat and reduced by the half clay layer within the peat. The equation accounts mainly for subsidence due to mineralization. Thus, it is valid for sites which were already drained for several years.

By default, the subsidence rate *SUB* [cm/ a] is calculated with

$$SUB = \left(0.147 \cdot \left(PT_{aw} + \frac{Cl}{2} \right) - 0.0006 \cdot \left(PT_{aw} + \frac{Cl}{2} \right)^2 + 0.05 \right) / 10 \cdot TF \cdot SF \cdot LUF \quad (4.7)$$

where *PT_{aw}* = peat thickness above the summer water table [cm], *Cl* = clay layer thickness near surface [cm], *TF* = temperature factor, *SF* = subsidence factor and *LUF* = Land use factor. Thus, the subsidence rate is rising with an increasing depth to mean summer water table and increasing air temperatures (figure 4.3).

Peat thickness above water table *PT_{aw}* [m] is calculated with

$$\text{if } PT < SWT/100 \quad \text{and if } PT > (Cl + 0.3) \quad \text{then } PT_{aw} = PT - Cl \quad (4.8)$$

$$\text{if } PT < SWT/100 \quad \text{and if } PT \leq (Cl + 0.3) \quad \text{then } PT_{aw} = PT \quad (4.9)$$

$$\text{if } PT \geq SWT/100 \quad \text{and if } PT > (Cl + 0.3) \quad \text{then } PT_{aw} = SWT/100 - Cl \quad (4.10)$$

$$\text{if } PT \geq SWT/100 \quad \text{and if } PT \leq (Cl + 0.3) \quad \text{then } PT_{aw} = SWT/100 \quad (4.11)$$

where *PT* = peat thickness [cm] and *SWT* = mean summer water table [cm below surface].

The temperature factor *TF* is calculated with

$$TF = -0.6 + 6.6 \cdot \frac{1}{2^{\frac{|T-25|}{8.17}}} \quad (4.12)$$

where *T* = mean air temperature [°C]. *TF* = 1 at an air temperature of 8.3°C (which is approximately the mean temperature of northern Germany). The temperature factor was developed for air temperatures between 0 and 25°C and was fitted to a realistic temperature sensitivity of the subsidence rate, using *Q₁₀* values. The *Q₁₀* value is the factor by which the respiration rate differs for a temperature interval of 10°C (FANG *et al.* 2005). For *TF*, *Q₁₀* values range from 2.7 (at 15 - 25°C) to 6.5 (at 0 - 10°C) and are comparable to those measured in the Netherlands by HENDRIKS & VERMEULEN (2000).

The subsidence factor *SF* is an input parameter to adjust the original equation (equation 4.6) to other sites with different conditions, such as varying precipitation, peat thickness, peat type, or bulk density.

By default, the land use factor *LUF* is set to one. With the land use category 'arable land', the land use factor is set to two.

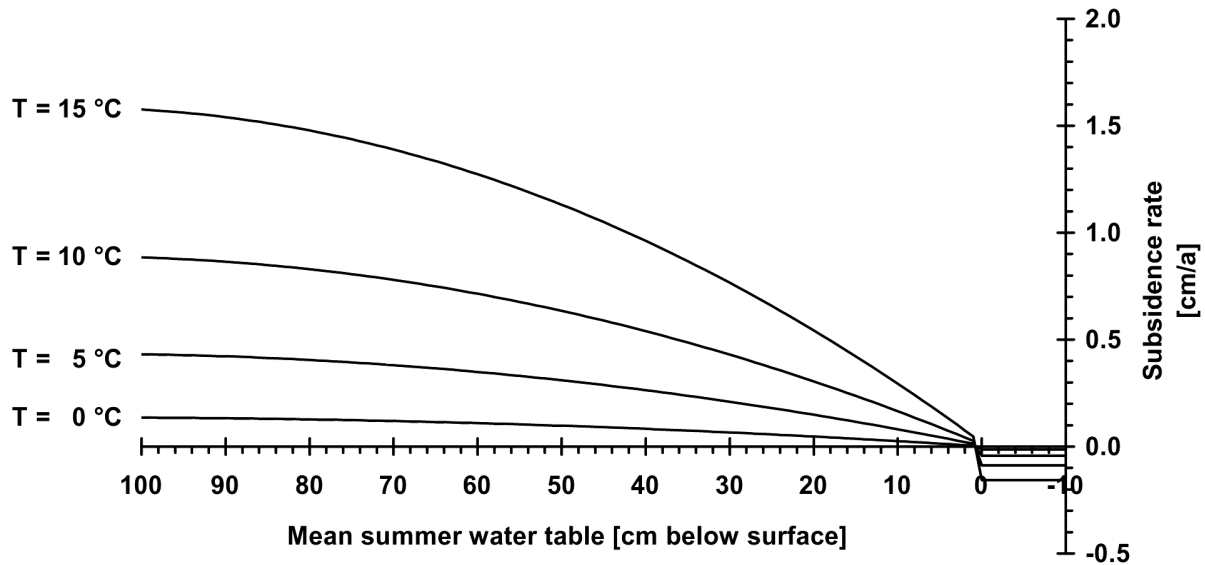


Figure 4.3: Example of how subsidence rate is calculated, depending on mean summer water table and air temperature for land use categories 2 - 12. Extended equation from RENGER *et al.* (2002)

Negative values of the subsidence rate account for **peat growth**. Peat growth starts if depth to mean summer water table is lower than 1 cm for more than ten years. In accordance to equation 4.5 (BLANKENBURG *et al.* 2001) and chapter 4.3.1.1 the peat growth rate in PMDSS is set to 0.07 cm/ a.

The **surface level** [m ASL] is newly calculated every year with the following rule: subsidence rate *SUB* is subtracted from surface level [m ASL] of the previous year.

If the **mean summer water table** is not calculated in the hydrology module (chapter 4.3.7), the initial mean summer water table is an input parameter. The summer water table may change over time due to subsidence and peat growth. Additionally, the summer water table may stay stable or change abruptly due to water management options independent from subsidence. Concerning the mean summer water table, the following rules are integrated into the model: In relation to the sea level, the mean summer water table [m ASL] SWT_{ASL} does not change significantly. If $SWT > 0$ cm, SWT_{ASL} is subtracted every year by the subsidence rate of the anaerobic peat layer SUB_{an} [cm/ a] which is calculated with

$$SUB_{an} = SUB \cdot 0.0002 \cdot PT_{bw} \quad (4.13)$$

where PT_{bw} = peat thickness below mean summer water table [cm]. Thus, the depth to mean summer water table SWT may decrease relative to the surface due to subsidence. If peat growth is simulated, SWT_{ASL} is rising together with the surface level. If the soil surface is ponded, the surface level is rising accounting for silting processes and SWT_{ASL} does not change until the surface level equals SWT_{ASL} . Additionally, the user can change the mean summer water table SWT in any model year to account for water management (in worksheet *Inp_TimeSeries*, see chapter 5.2.3 on page 62).

4.3.2 Land use

4.3.2.1 State of knowledge

Worldwide, approximately 80% of original tropical and non-tropical mires are still under pristine conditions. The other 20% were altered mainly for agricultural and silvicultural land use, but also for peat extraction, urbanization, and inundation (JOOSTEN & CLARKE 2002). In Europe, 52% of the original peatland area of 617 000 km² has been converted mainly for agriculture and forestry use during the last century. The largest areas of peatlands used for agriculture are in Russia, Germany, Belarus, Poland, and the Ukraine (RYDIN & JEGLUM 2006). The most intensive conversions for agriculture as percentage of total peatland area of a country are found in Hungary (98%), Greece (90%), Germany, and the Netherlands (85% each) as well as in Denmark, Poland, and Switzerland (70% each), and the Ukraine (50%). The largest areas of drainage for forestry are found in Finland, Russia, and Sweden.

BYRNE *et al.* (2004) gathered literature values which help to differentiate types of peatland use. Agricultural land use is distinguished into grass and crop area. In EUROPEAT project countries, peatlands converted into agriculture are mainly utilized as pasture or meadow (table 4.3). In Sweden agricultural peatlands are only used for crops. More, in Germany and Great Britain, considerable parts are used as arable land. The conservation and wise use of peatlands have been getting more attention for several years now. At an international level, this is mainly encouraged within the Ramsar Convention by the Guideline for Global Action on Peatlands (GGAP). Further support is given by the Convention on Biological Diversity (CBD).

Intensive land use of peatlands is always connected with high costs for drainage (TREPEL 2003, SCHOUWENAARS 2002, SUCCOW 2001). Due to the lowering of the surface level, costs are increasing over time. This can be observed especially at sites which subsided already below sea level. Thus, especially at marginal peatland sites, it increasingly occurs that drainage is not worthwhile anymore. Hence, peatlands are used less intensively or left abandoned (LENSCHOW & THIEL 2000). Other peatlands are used more intensively to get economically justifiable harvests.

Table 4.3: Estimated peatland use of EUROPEAT project countries (after BYRNE *et al.* 2004).

Country	Mire area ^a [km ²]	Forestry area ^a [km ²]	Grass area ^b [km ²]	Crop area ^b [km ²]	Peat cut area ^c [km ²]	Residual ^d [km ²]
Germany	390 ^e	2 189 ^e	8 559 ^e	4 724 ^e	300	358
Great Britain	1 000	6 000	310 ^f	410 ^f	40	9 740
Netherlands	150	0	2 000 ^f	0 ^f	0	200
Norway	22 000	4 200 ^g	1 900	0 ^g	20	-120
Poland	2 000	1 270	7 565	55	10	1 600
Sweden	55 000	14 100	0	3 000	110	-1 210

^aJOOSTEN & CLARKE (2002)

^bLAPPALAINEN (1996)

^cSELIN (1999)

^dResidual area to match total peatland area, which is given in column '2002 peatland area' in table 2.1 (JOOSTEN & CLARKE 2002).

^eNew GIS-based estimate from German Federal Agricultural Research Centre (FREIBAUER *et al.* in prep.).

^fLiterature value gives total agricultural area only. Distribution between grassland and cropland use based on expert judgement.

^gCorrected after RYDIN & JEGLUM (2006)

4.3.2.2 Module description

The PMDSS land use module was developed on the basis of the state of knowledge (summarized in the last chapter) and will be described in the following paragraph. The land use category is an input parameter for the initial state and the second model year. Further land use change is calculated in worksheet *Mod_LU*.

The selection of land use categories was carried out with regard to the differentiation of important agricultural land use types on peat soils, the differentiation of vegetation types, and the associated parameter fertilizer (link to nitrogen module, chapter 4.3.5.2). A further aim for selecting land use categories was to consider agricultural utilization as well as extensification, rewetting, and conservation. In accordance with the expert system WETTRANS (TREPPEL *et al.* 2004), the following land use categories were chosen (listed in detail in table 5.3 on page 60):

- arable land,
- forest,
- intensive and moderate grassland (mowing and/ or grazing),
- grassland use with the aim of nature conservation, and
- abandonment (short or long time).

In order to relate land use categories with vegetation types (needed for vegetation module, chapter 4.3.3), typical land uses are specified for the categories in detail (table 5.3 on page 60, HOLSTEN 2006). In PMDSS, the land use category 'nature conservation management' means that the site is exclusively managed after requirements of nature conservation, especially for conservation of small sedge reeds (and species rich wet meadows) with potential of occurrence of many red list plant species.

A simple rule to describe land use change is used: if the mean summer water table is lower than a defined water table limit, the actual land use category is set to a potential next land use category (see parameters in table 5.5). The water table limit can be adjusted by the user in the worksheet *Input_Tab*. When land use is changing, associated parameters such as fertilizer, harvested proportion of biomass, and target vegetation type are also changing in PMDSS (compare tables 5.5 and 5.3 and the relevant chapters 4.3.5 and 4.3.3).

4.3.3 Vegetation module description

This chapter gives a summary of the vegetation module in worksheets *Mod_veg1* to *Mod_veg4*, developed by Bettina Holsten (HOLSTEN 2006). The vegetation module is a deviation of Markov chains which uses constant transition probabilities to calculate the vegetation development within 50 years. Transition probabilities are specified between discrete states in the observed system. The basic units are plant species groups. The output parameters are 'conservation value', 'potential standing crop', 'economic value', and 'N₂-fixation'. Further parameters needed for other modules are calculated in worksheet *Mod_Veg5*.

Parameters such as water table, land use intensity, water source, water table dynamics, soil characteristics and nutrient availability are known to determine species composition in plant communities (ELLENBERG 1996, DEN HELD *et al.* 1992, EVERTS & DE VRIES 1991).

So far, different attempts have been made to define plant species groups with similar characteristics. Sufficient results were received with taking the abandonment and intensification groups defined by SCHRAUTZER & JENSEN (1999). About 3000 vegetation releves of grasslands on peatlands in northern Germany (JENSEN & SCHRAUTZER 1999) were analyzed in their plant species composition. Groups of plants with similar reactions mainly to abandonment and different land use intensities were identified. Additionally reaction, nitrogen, and moisture values of Ellenberg (R-, N- and F-values, ELLENBERG 1996) have been used for classification.

4.3.3.1 Coverage by plant groups

The basis of the vegetation module is the calculation of the coverage of plant groups in worksheet *Mod_veg1*.

30 vegetation releves from the most important vegetation types on managed peat soils were taken from a database of northern Germany, including *Alnus* forests, base rich small sedge meadows, base poor small sedge meadows, abandoned forage meadow/ wet meadow, reed fields, forage meadows, wet meadows, and *Urtica*-communities on abandoned sites. The average coverage of plant species for each vegetation type was calculated. Plant species with similar ecological characteristics were summarized to plant groups, which led to the formation of 85 different plant groups. The four criteria by which the plant species were grouped are described below:

1. Abandonment category

SCHRAUTZER & JENSEN (1999) distinguished 11 different types of plant response to abandonment in northern Germany. In PMDSS, the four main categories A, B, C, and D are used. Plant species not mentioned by them were classified according to ELLENBERG (1996): plant species occurring in forest vegetation types were classified as D, typical plants of disturbed places such as typical field species were classified as A and the others received no abandonment value. The abandonment categories are:

- A = highest cover in managed stands, decreasing after abandonment, later missing
- B = highest cover in managed stands, decreasing after abandonment
- C = no pronounced changes of cover during succession
- D = lowest cover in managed stand or missing, increasing after abandonment

2. Intensification category

The intensification categories defined by SCHRAUTZER & JENSEN (1999) were used and two more classes for field and forest species have been added. Species which were assigned no value by the authors received values from ELLENBERG (1996) in case they were found in disturbed places (E) or forests (F). Categories in PMDSS are:

4 Development of the decision support system PMDSS

- A (SC) = highest cover in small sedge meadows, decrease in wet meadows, missing in forage grassland
- B (CM) = highest cover in small sedge meadows, decrease in wet meadows and forage grassland
- C (CE) = highest cover in eutrophic wet meadows, decrease in small sedge meadows and forage grassland
- D (RA) = highest cover in forage grassland, decrease in small sedge meadows
- E = highest cover in fields, decrease in grasslands
- F = highest cover in forests, decrease in grasslands

3. Water source

Different water sources were distinguished by using Ellenberg R- and N-values (ELLENBERG 1996). R-values characterize the reaction of plants to base saturation; the N-value indicates nutrient demand. In PMDSS, 'water source' is an input parameter and only has influence on the development of small sedge meadows. Three water sources are distinguished:

- Rain water: R-value 1-4 (base poor) and N-value 1-3 (nutrient poor)
- Mixed water: all other combinations of R- and N-values and missing indication
- Calcareous ground water: R-value 7-9 (base indication)

4. Water table

On sites of moderate wetness with higher human impact land use intensity dominates the plant species composition. Because PMDSS is developed for managed peatlands with agricultural land use activity, Ellenberg moisture values (ELLENBERG 1996) were only used to distinguish between plants preferring very wet and dry sites to model vegetation development after rewetting:

- D: preferring dry sites (F-Value 1-9)
- F: flooding tolerant (F-Values > 9)

A list of the plant species with the associated values is given in Annex C.

In the model, the coverage of each plant group is modelled annually over a time period of 50 years. Forcing functions of the vegetation module are 'land use category', 'mean summer water table' and 'water source'. Each land use category is associated with a vegetation type (table 5.3). Internally, the vegetation module calculates with land use intensities (numbers between 0 and 1), which are also associated with land use categories and corresponding vegetation types. PMDSS starts with the average cover of each plant group for the selected vegetation type. Alternatively, it is possible to include a vegetation relevee from the investigated site. The calculation of the coverage of each plant group every year is done by multiplying the coverage of the previous year with a transition probability factor. The transition probabilities of the plant groups were determined for a defined set of land use changes as follows. The model is based on the assumption that constant rates of change lead to a transition from one state to another. As a starting point, the average vegetation type characteristic for a specific land use category is chosen. The final vegetation type is chosen according to the land use category defined for the second model year in PMDSS. The time necessary to reach the new stable vegetation community is a literature-based estimation. The transition probability of a plant group tp_{pg} is calculated with

$$tp_{pg} = (COVst_{pg} \cdot COVtar_{pg})^{1/y}$$

where $COV_{st_{pg}}$ = coverage of plant group in starting year [0-1], $COV_{tar_{pg}}$ = coverage of plant group in target vegetation type [0-1] and y = expected time for change in coverage [years].

General calculation rules include the possibility of new plant species to enter the site by setting the cover of each plant group, which is not present in the first year, to 0.0001. The cover of every single plant group is limited to about 50%.

The model was calibrated for a restricted number of modelled cases with some available long term data (4 to 25 years) from sites on peat soil where it is guaranteed that the land use was stable every year (HOLSTEN 2006). The model was adjusted according to the results.

4.3.3.2 Conservation value

The conservation value is calculated in worksheet *Mod_vegl* for model year one and 50.

The conservation value is based on the national red list of threatened plant species of the different project partner countries (Germany, Great Britain, The Netherlands, Norway, Poland, Sweden). The description was converted to numbers and a multiplication factor was associated with each category so that very rare species are weighted higher than near threatened species. The conservation value of a plant group $cons_{pg}$ is calculated as follows:

$$cons_{pg} = \left(\sum_{i=0}^n WRLS_{sp} \right) \cdot COV_{pg} \quad (4.14)$$

where $WRLS_{sp}$ = weighted red list status of plant species sp , COV_{pg} = coverage of the plant group pg , n = amount of species with red list status within a plant group. To get the absolute conservation value the conservation value of the plant groups are summed up. If land use is arable land, the conservation value is set to zero, because arable fields have no plant species which are characteristic for peat soils.

As output of PMDSS, the relative conservation value is used, where the maximum absolute conservation value of the standard vegetation type in PMDSS is set to one. For each country the maximum value was found in small sedge communities on base rich sites. Because the maximum values between the countries vary, a maximum was defined for each country separately. Further model output is the text interpretation of the relative conservation value as follows:

< 0.125	Low conservation value
≥ 0.125 and < 0.25	Medium conservation value
≥ 0.25 and < 0.5	High conservation value
≥ 0.5	Very high conservation value

Text interpretation of the difference of relative conservation value of year 50 and year 1 is as follows:

≤ 0.125 and ≥ -0.125	No significant change
< -0.125 and ≥ -0.49	Moderate loss
< -0.49	Loss not acceptable
> 0.125 and ≤ 0.49	Moderate improvement
> 0.49	Important improvement

The analysis of the percentage of communities protected by the European Habitats Directive (RIECKEN *et al.* 1994) resulted in an extra text output as 'Recommendations for planning': if the vegetation type 'small sedges' was selected for the initial state, the output is 'vegetation type protected by the FFH directive'.

In case 'alder forests' or 'abandoned grassland' was selected, the output is 'some vegetation communities protected by the FFH directive'.

The vegetation releves from the site will always improve the reliability of the simulation results.

It is important to stress the point that the conservation value accounts for the potential habitat suitability of a site for red list plant species. On the one hand, the model starts with an average conservation value for the selected vegetation type (which can be different from the actual one if no own vegetation relevee was included and because average values were defined for each plant group). On the other hand, if rare species are really able to colonize the site, depends on seed bank of the site and dispersal of plants from neighbouring sites (JENSEN 1998, MAAS & SCHOPP-GUTH 1995).

4.3.3.3 Productivity

'Potential standing crop' and 'economic value' are calculated in worksheet *Mod_Veg3*. In worksheet *Mod_Veg5*, 'potential standing crop production' is calculated.

The **potential standing crop** is an intermediary result for the economic value. It is based on average plant height and average amount of dry matter of each vegetation type. Potential standing crop of plant group SC_{pg} [t dry matter ha⁻¹ a⁻¹] was calculated with

$$SC_{pg} = \frac{\sum_{sp=1}^n (h_{sp} \cdot COV_{sp})}{SC_{vt}} \quad (4.15)$$

where h_{sp} [cm] = average height of a plant species taken from the database BioBase2003NC (CBS 2003), COV_{sp} [%] = cover of a plant species within a vegetation type and SC_{vt} [t dry matter ha⁻¹ a⁻¹] is the average standing crop of a vegetation type from literature data (see footnote a in table 4.6 on page 35). The calculated amount of dry matter produced by each plant group varies between the vegetation types.

For every year and each plant group, a conversion factor Fco_{pg} is determined for multiplying with coverage to get potential standing crop. The first year is starting with the potential standing crop distribution of the selected vegetation type. In case a new vegetation relevee is entered in the model, the model starts with the average potential standing crop distribution of all vegetation types. The conversion factor is calculated with $Fco_{pg} = SC_{pg}/COV_{pg}$, where SC_{pg} = potential standing crop and COV_{pg} = coverage of the plant group pg . If land use of the second year is different from the first year, the target factor is calculated with $Fta_{pg} = SCav_{pg}/COVav_{pg}$ where for the potential standing crop $SCav_{pg}$ and the coverage $COVav_{pg}$ average values of all vegetation type are used, otherwise $Fta_{pg} = Fco_{pg}$. The potential standing crop of each year is calculated with $SC_{pg} = COV_{pg} \cdot Fco_{pg}$. When changes in land use intensity are modelled, 0.1 is added to or subtracted from factor Fco_{pg} each year until $Fco_{pg} = Fta_{pg}$.

If the model starts with a forest or when cover of trees is getting higher than 30%, an average yearly increase of wood of 3.5 t/ha is added to the potential standing crop of the plant groups with *Alnus*, *Betula*, or *Salix*. If a water level of more than 5 cm above surface is chosen, the typical standing crop and cover of reed is selected to calculate the target factor Fta_{pg} .

The **economic value** is defined as a combination of cost of harvest, quality, and quantity of harvest (table 4.4):

- High value: cost for harvest low, quality high and quantity high
- Low value: cost for harvest high, quality low and quantity low
- Medium value: other combinations of values

Table 4.4: Matrix to determine different aspects of economic value (LU = land use category).

	High	Medium	Low
Cost for harvest	Summer water table > 14 cm below surface, wood harvest	Summer water table 14 - 25 cm below surface	Summer water table > 25 cm below surface
Quality of harvest	Field crops (LU = 1), food for milk production (LU = 3, 4, 5), reed (> 5 t dry matter ha ⁻¹ a ⁻¹), old alder wood	Wood for energy, food for cattle (LU = 6, 7, 8)	Hay for horses (LU = 9), energy production
Quantity of hay	Standing crop > 7 t dry matter ha ⁻¹ a ⁻¹	Standing crop 7-4 t dry matter ha ⁻¹ a ⁻¹	Standing crop < 4 t dry matter ha ⁻¹ a ⁻¹

If land use is forest, economic value is given as potential, because a cutting of the trees is not modelled.

Potential standing crop production *SCPRO* is derived from 'potential standing crop' and is calculated in worksheet *Mod_Veg5*. It is used within the nitrogen module (chapter 4.3.5.2). In difference to 'potential standing crop', *SCPRO* is accounting only for the additional produced annual biomass of the growing forest. Additionally, *SCPRO* is estimated via a simple rule up to year 100.

4.3.3.4 N₂-fixation

N₂-fixation [kg N ha⁻¹ a⁻¹] is calculated in worksheet *Mod_veg1* and is needed for the nitrogen module, where a maximum value is set for this parameter (chapter 4.3.5.2.1 on page 37). Calculation is based on the following N-fixation rates mentioned in the literature (compare chapter 4.3.5.1 on page 33):

- Alder wet: 70-85 kg N ha⁻¹ a⁻¹ (DITTERT 1992)
- Alder dry: 40-45 kg N ha⁻¹ a⁻¹ (DITTERT 1992)
- 1% cover of legumes: 3-(5) kg N ha⁻¹ a⁻¹ (RIEDER 1983)

The alder forest vegetation plots used in the model had a cover of about 50% *Alnus glutinosa*. To derive N-fixation by alder, the percentage cover of the plant group with alder is multiplied with the factor 70/ 50 kg N ha⁻¹ a⁻¹ at wet sites (depth to mean summer water tables < 20 cm) and 40/ 50 kg N ha⁻¹ a⁻¹ at dry sites (depth to mean summer water tables ≥ 20 cm).

For each plant group, the percentage cover of the legume species was calculated from the average of all vegetation relevees. N-fixation of legumes was calculated by multiplying the average legume cover of each plant group by 3 kg N ha⁻¹ a⁻¹.

4.3.4 Carbon dioxide and methane emission

4.3.4.1 State of knowledge

"It has been estimated that around a third of the carbon in the world's soils is stored in peatlands, an amount that is more than half the current atmospheric stock of carbon dioxide" (RYDIN & JEGLUM 2006: 238). In contrast, peatlands cover 3% of the world's land area. This illustrates the importance of peatlands within the global carbon circulation.

In peatlands, carbon is stored in biomass, litter, and peat. A rough estimation is that 1 g dry biomass contains 0.5 g carbon (CALOW 1998 in RYDIN & JEGLUM 2006). CO₂ is sequestered from the atmosphere by plant photosynthesis and transformed into biomass. After plant death, carbon is stored in peat. In peatlands, the organic carbon is subject to aerobic and anaerobic mineralization processes. Peat decomposition under anaerobic conditions leads to CH₄-formation. Under aerobic conditions it leads to CO₂-formation. Thus CH₄-emission occurs at high water tables. More, CO₂-emission increases with drainage depth. In drained peatlands, CH₄ formed in deeper layers oxidizes to CO₂ in the aerobic layers. Mineralization of peat runs much faster under aerobic conditions than anaerobic conditions. Under pristine conditions, storage of carbon through sequestration of CO₂ is usually higher than loss of carbon through peat mineralization (mainly CH₄-emission), which is connected with peat growth (chapter 4.3.1.1 on page 16). In drained peatlands peat mineralization is the main contributor to subsidence in the long term (chapter 4.3.1.1).

Commonly used methodologies to measure gaseous fluxes of CO₂ and CH₄ between surface and atmosphere are summarized by BYRNE *et al.* (2004). Most commonly used is the chamber method, where a chamber is placed on the soil surface and is monitoring the gas exchange from the surface for some minutes. The eddy correlation method provides a non-intrusive and continuous measure of the flux at field to landscape scale level. As the application of those methods is connected with high costs, emission rates and carbon balance are often estimated with indirect methods. On drained peatlands, CO₂-emission is derived from subsidence rates. The long-term apparent rate of C accumulation (LORCA) (CLYMO *et al.* 1998) is derived from age determination. The measured values obtained with direct methods show an extremely high variability. The variation coefficients reach more than 100% (LIVINGSTON & HUTCHINSON 1995 in AUGUSTIN 2001). More, emission rates during wintertime may be underestimated or ignored, as only few wintertime measurements have been carried out over peatland (BYRNE *et al.* 2004).

For the simulation of carbon dioxide and methane emission, several process-based **models** have been developed, including both gases (VAN HUISSTEDEN *et al.* 2006, STEINMANN *et al.* 2004) or only CH₄ (KETTUNEN 2003, ARAH & STEPHEN 1998, SEGERS 1998, WALTER *et al.* 1996).

CO₂-emission

The most important factor on CO₂-emission is the depth to water table. Further influencing factors are climate, temperature, peat thickness, peat type, bulk density, and pH value (RYDIN & JEGLUM 2006, VAN HUISSTEDEN *et al.* 2006, RENGER *et al.* 2002, AUGUSTIN 2001, SILVOLA *et al.* 1996, NYKÄNEN *et al.* 1995, GORHAM 1995). In cool temperate bogs, ecosystem respiration depends mainly on temperature of peat (LAFLEUR *et al.* 2005).

In the literature, CO₂-emission values of drained minerotrophic peatlands vary between 1900 and 6700 kg CO₂-C ha⁻¹ a⁻¹ and sequestration values vary between 140 and 2250 kg CO₂-C ha⁻¹ a⁻¹ (table 4.10 on page 43).

Usually, CO₂-emission increases with increasing drainage depth and reaches a maximum value at a depth to water table of 80 to 110 cm (MUNDEL 1976 in AUGUSTIN 2001: 33). At deeper water tables mineralization, decreases due to temporary lack of water.

RENGER *et al.* (2002) developed regression equations for CO₂-emission for four different types of minerotrophic peatlands in northeast Germany, each with land use type grassland. They correspond to the equations of RENGER *et al.* (2002) for the decrease of peat thickness (equation 4.6 on page 18). The CO₂-emission $CO2_C_{Renger}$ [kg ha⁻¹ a⁻¹] of peatland type a (Erd-fen with peat thickness ≥ 1 m; confer explanation to equation 4.6) is calculated as follows:

$$CO2_C_{Renger} = 121 \cdot SWT - 0.482 \cdot SWT^2 - 121 \quad (4.16)$$

where SWT = mean summer water table [cm below surface]. Further explanation is given in chapter 4.3.1.1 on page 16.

CH₄-emission

Methane is produced by methanogens, organisms growing under anaerobic conditions near the water table. Their main zone shifts up and down with the water table. More, the production depends on the amount and quality of organic fresh material (litter) and root exudation in the anoxic zone (RYDIN & JEGLUM 2006). From the production zone, methane moves upwards through diffusion or bubbles. As methane passes through the oxic layer, it is consumed by bacteria (methanotrophs) and partly oxidized to CO₂. Depending on the thickness of the oxic layer, only a part or all methane is consumed. A considerable fraction of the CH₄ is transported through aerenchymatous plants, bypassing the oxic peat layer (RYDIN & JEGLUM 2006).

Those processes explain that as for CO₂-emission, the most important factor influencing methane emission is the water table. Further influencing factors are amount and quality of organic material, vegetation type, climate, temperature, and peat thickness (VAN HUISSTEDEN *et al.* 2006, KETTUNEN 2003, JOOSTEN & CLARKE 2002, SOMMER & FIEDLER 2002, TREPPEL 2000, SCOTT *et al.* 1999, KOMULAINEN *et al.* 1998, LIEN *et al.* 1992).

Measurements show that methane emission is increasing with increasing water table (table 4.5). At high water tables, in pristine and rewetted peatlands, methane emission varies between 118 to 640 kg CH₄-C ha⁻¹ a⁻¹. Methane fluxes in North American peatlands vary in a similar range, between -3 and 830 kg CH₄-C ha⁻¹ a⁻¹ (BRIDGHAM *et al.* 2006). Significant methane emission starts at depths to water table between 10 and 20 cm. LE MER & ROGER (2001) suggest a negative logarithmic correlation of methane emission with depth to water table (for water tables between 0 and 60 cm below surface). The summer period is connected with higher temperatures and thus higher methane emission rates (KOMULAINEN *et al.* 1998, LIEN *et al.* 1992, CRILL *et al.* 1992). Hence, the mean summer water table is important for annual average CH₄-emission. Larger dry periods throughout the summer lead to a significant decrease of CH₄-emission (BLODAU & MOORE 2003, KETTUNEN 2003, VAN DEN BOS 2003).

The importance of peat thickness concerning CH₄-emission is not fully understood. As the main production of methane occurs in the upper horizon, the first 5 to 40 cm of the peat profile contribute most to methane emission (KETTUNEN 2003, LE MER & ROGER 2001, CLYMO & PEARCE 1995). The thicker the anaerobic peat layer gets, the more methane can be produced (MEYER *et al.* 2001). Model experiments by STEINMANN *et al.* (2004) suggest that peat thickness plays, if at all, only a role up to a depth of 5 m.

4.3.4.2 Module description

The PMDSS carbon module was developed on the basis of the state of knowledge (summarized in the last chapter) and will be described in the following paragraphs.

By default, CO₂-emission and CH₄-emission are calculated in worksheet *Mod_C* as described in this chapter. PMDSS is also able to calculate CO₂-emission with an equation, inserted by the user into worksheet *Mod_Adj* (if parameter 'Inserting new equations in Mod_Adj' was set to 1).

Table 4.5: Methane emissions of peatlands in Europe and Canada.

Location, vegetation	Annual water table (mean; amplitude) [cm below surface]	CH ₄ -C emission [kg CH ₄ -C ha ⁻¹ a ⁻¹]	Source
Germany			
Sowing grassland, Friedlitzender Große Wiese	10 to 60	0.6 to 3.5	AUGUSTIN <i>et al.</i> 1996 ^a
Phalaris, Friedlitzender Große Wiese	10 to 40	10.6	AUGUSTIN <i>et al.</i> 1996 ^a
Typha, Friedlitzender Große Wiese	0 to 10	293	AUGUSTIN <i>et al.</i> 1996 ^a
Alder carr, Belau	0; -10 to 30	143 ^b	PAPKE & RUSCH 1995 ^a
Flood pasture, Belau	10; 5 to 35	122 ^b	PAPKE & RUSCH 1995 ^a
Alder carr, Mißencheberg	60	-1.4 ^c	AUGUSTIN 2003
Alder carr, Mißencheberg	2 to 40	1.7	AUGUSTIN 2003
Reed, Sernitz-Welse-Niederung	0 ^d	640	AUGUSTIN 2003
Tall sedge reed, Lange Dammwiesen	0 ^d	179	AUGUSTIN 2003
The Netherlands			
Wet pasture	50; 15 to 85	-0.3 to -0.4 ^c	VAN DEN POOL - VAN DASSELAR & OENEMA 1996 ^a
Wet pasture	35; 2 to 70	0	
Tall sedge reed, wet meadow	10; 0 to 30	^b 125	
Finland			
Small sedge reed	10; 5 to 25	149 to 259	NYKÄNEN <i>et al.</i> 1995 ^a
Intensive meadow	30; 20 to 117	1 to 2	NYKÄNEN <i>et al.</i> 1995 ^a
Floating mat	5; 0 to 10	190 to 420	MARTIKAINEN <i>et al.</i> 1995 ^a
Bog ^g	10; 5 to 35	20 to 40	MARTIKAINEN <i>et al.</i> 1995 ^a
Birch carr	30; 0 to 57	-0.3 ^c to 0.4	MARTIKAINEN <i>et al.</i> 1995 ^a
Fen ^e , Sphagnum, shrubs, mosses	36.5 ^f	1.9 ^b	KOMULAINEN <i>et al.</i> 1998 ^a
Fen ^e , Eriophorum vag., Sphagnum	9.0 ^f	10.4 ^b	KOMULAINEN <i>et al.</i> 1998 ^a
Fen ^e , Sphagnum, shrubs, mosses	43.5 ^f	0.1 ^b	KOMULAINEN <i>et al.</i> 1998 ^a
Fen ^e , Eriophorum vag., Sphagnum	20.5 ^f	20.3 ^b	KOMULAINEN <i>et al.</i> 1998 ^a
Tall sedge reed ^e	8 ^f	118 ^b	MINKKINEN <i>et al.</i> 2004 ^a
Sphagnum fuscum pine bog ^g	28 ^f	7 ^b	MINKKINEN <i>et al.</i> 2004 ^a
Canada			
'Open bog' community ^g , Chamaedaphne shrub	-2.4 ^f	237.6 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Chamaedaphne shrub	23 ^f	3.4 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Chamaedaphne shrub	28.2 ^f	-0.1 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Carix oligosperma	13.3 ^f	43.2 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Carix oligosperma	19.3 ^f	1.5 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Carix oligosperma	37.5 ^f	0.0 ^b	SCOTT <i>et al.</i> 1999
'Open bog' community ^g , Chamaedaphne/Ledum shrub	5.9 ^f	71.6 ^b	SCOTT <i>et al.</i> 1999

^aTaken from TREPPEL (2000)^bCalculated from daily mean values^cNegative values account for sequestration^dAssumed value^eFen = minerotrophic peatland^fWater table during ice free season^gBog = ombotrophic peatland

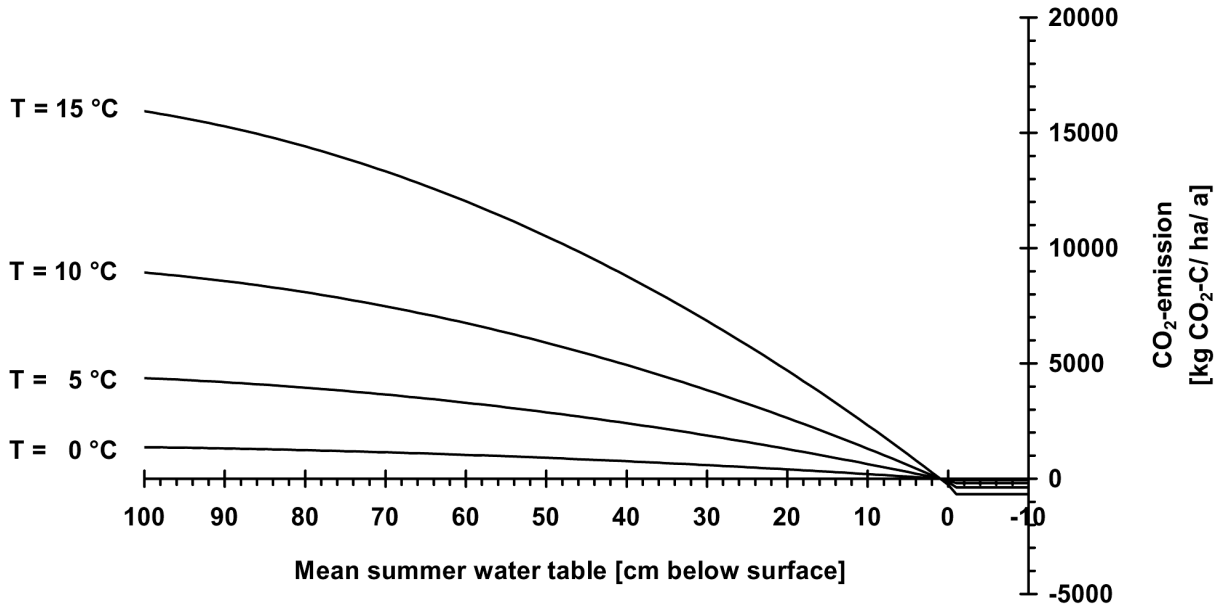


Figure 4.4: Example of how CO₂-emission is calculated, depending on the mean summer water table and air temperatures for land use categories 2 - 12. Extended equation from RENGER *et al.* (2002).

CO₂-emission

For the calculation of CO₂-emission in PMDSS, the corresponding equation to subsidence rate of RENGER *et al.* (2002) was taken as a basis (equation 4.16). As oxidation is the main contributor to long-term subsidence, the calculation of subsidence is strongly correlated with the calculation of CO₂-emission. RENGER *et al.* (2002) assume that oxidation equals CO₂-emission.

For the use in PMDSS, equation 4.16 was extended with the same factors as the subsidence rate (equation 4.7 on page 19): temperature factor, subsidence factor and land use factor. Additionally, the mean summer water table is reduced by mineral layers above the mean summer water table and below the peat and reduced by the half clay layer within the peat. The equation is valid for sites which were already drained for several years.

By default, CO₂-emission $CO2_C$ [kg CO₂-C ha⁻¹ a⁻¹] is calculated with

$$CO2_C = \left(121 \cdot \left(PTaw + \frac{Cl}{2} \right) - 0.482 \cdot \left(PTaw + \frac{Cl}{2} \right)^2 - 121 \right) \cdot TF \cdot SF \cdot LUF \quad (4.17)$$

where $PTaw$ = peat thickness above the summer water table [cm] (equations 4.8 - 4.11 on page 19), Cl = clay layer thickness near surface [cm], TF = temperature factor (equation 4.12 on page 19), SF = subsidence factor and LUF = Land use factor. Thus, CO₂-emission is rising with increasing depth to mean summer water table and increasing air temperatures (figure 4.4). Factors are described in detail in chapter 4.3.1.2 on page 18. At an air temperature of 8.3°C, 0.1 cm subsidence equals on average an emission of 790 kg CO₂-C ha⁻¹ a⁻¹.

Negative values account for **CO₂-sequestration**. If the mean summer water table is above the surface ($SWT < 0$ cm), CO₂-sequestration is calculated with

$$CO2_C = -300 \cdot TF \quad (4.18)$$

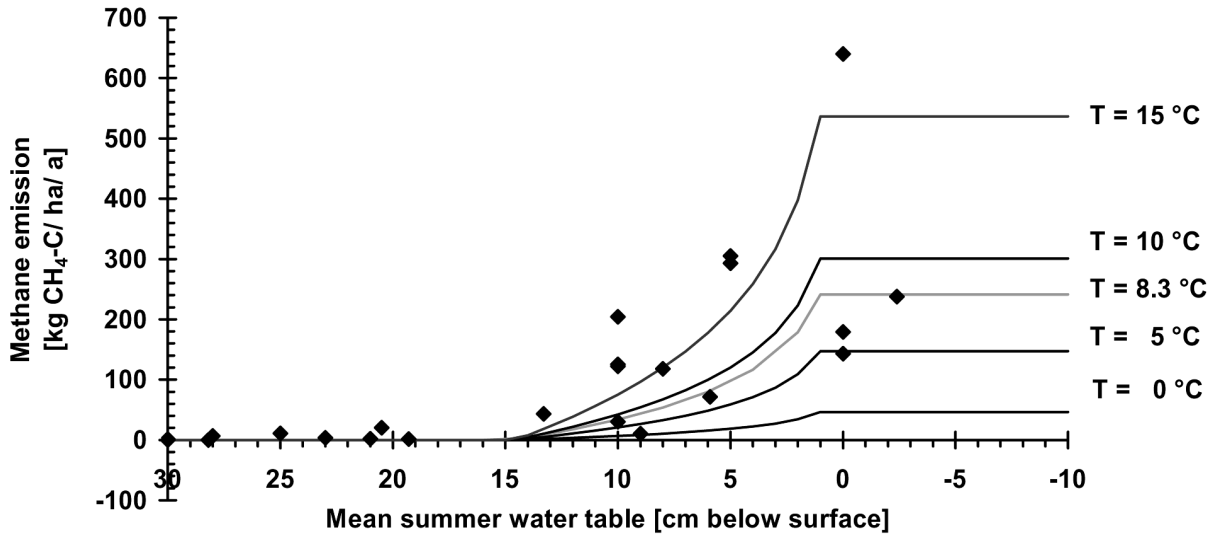


Figure 4.5: Example of how CH₄-emission is calculated, depending on mean summer water table and air temperature. Dots are the literature values from table 4.5, whereas they are partly mean annual values.

The standard value for sequestration of 300 kg CO₂-C ha⁻¹ a⁻¹ at $TF = 1$ (air temperature of 8.3 °C) corresponds to values from pristine peatlands (table 4.10 on page 43).

CH₄-emission

The calculation of methane emission is based on emissions of minerotrophic peatlands (table 4.5). A logarithmic function was assumed, fitted to the literature values and extended with the temperature factor TF (figure 4.5). In PMDSS, CH₄-emission $CH4_C$ [kg CH₄-C ha⁻¹ a⁻¹] at depths to mean summer water tables between 1 and 14 cm is calculated with

$$CH4_C = (-90 \cdot \ln(SWT) + 241) \cdot TF \quad (4.19)$$

and at depths to mean summer water tables less than 1 cm with

$$CH4_C = 241 \cdot TF \quad (4.20)$$

where SWT = mean summer water table [cm below surface] and TF = temperature factor (equation 4.12 on page 19). At $SWT > 14$ cm below surface CH₄-emission is set to zero. Thus, CH₄-emission is rising with decreasing depth to mean summer water table and increasing air temperatures (figure 4.5). The standard value for methane emission of 241 kg CH₄-C ha⁻¹ a⁻¹ at $TF = 1$ (air temperature of 8.3 °C) at a depth to mean summer water tables < 1 cm is a result of fitting and smoothing the curve and lies within the range of measured emissions at high water tables (chapter 4.3.4.1).

4.3.5 Nitrogen balance

4.3.5.1 State of knowledge

In an ecosystem, the nutrient budget is balanced if input equals output. A general nitrogen balance includes input pathways (fertilizer, deposition, fixation, groundwater, surface water), output pathways (harvest, denitrification, volatilization, discharge with water) and system internal concentration changes (mineralization, immobilization) (figure 4.6, TREPEL 2000). This balance can be applied to different spatial and temporal scales.

The development of the nitrogen module is based on the nitrogen budget (SCHRAUTZER 2004, TREPEL & KLUGE 2004, TREPEL *et al.* 2000, TREPEL 2000, KOERSELMANN & VERHOEVEN 1992).

Generally, pristine mires are considered to be a nutrient 'sink' in the landscape. Strictly speaking, the term 'sink' describes the physical and biological accumulation of nutrients. In addition, peatlands as ecotones between land and water provide good conditions for biological, biochemical, and chemical transformations processes leading to a reduction of nutrient concentrations in soil water (TREPEL 2004b, TREPEL 2000). Thus, on the catchment scale peatlands have a high potential for nitrogen retention. Nitrogen retention occurs where the discharge of nitrogen is lower than the inflow with surface water and groundwater.

Atmospheric deposition includes wet deposition (with precipitation) and dry deposition (dust particles and gases). Sources of deposition and immission are motor traffic and industry as well as ammonia gases from intensive livestock husbandry (SCHIMMING 2004). N-deposition varies between locations depending on their distance to sources, wind speed, wind direction, land cover, and micro-climate, especially due to the vegetation type. GAUGER *et al.* (2002) estimated the total deposition of nitrogen ($\text{NH}_x\text{-N} + \text{NO}_y\text{-N}$) in Germany from 1995 - 1999 with $30 \text{ kg N ha}^{-1} \text{ a}^{-1}$ in average. Locally, it is varying between 6.3 and $173.8 \text{ kg N ha}^{-1} \text{ a}^{-1}$. The mean contribution of wet deposition to total N-deposition (1990 to 1999) was about 30%. 70% are due to dry deposition respectively. Mean nitrogen deposition of around 230 forest

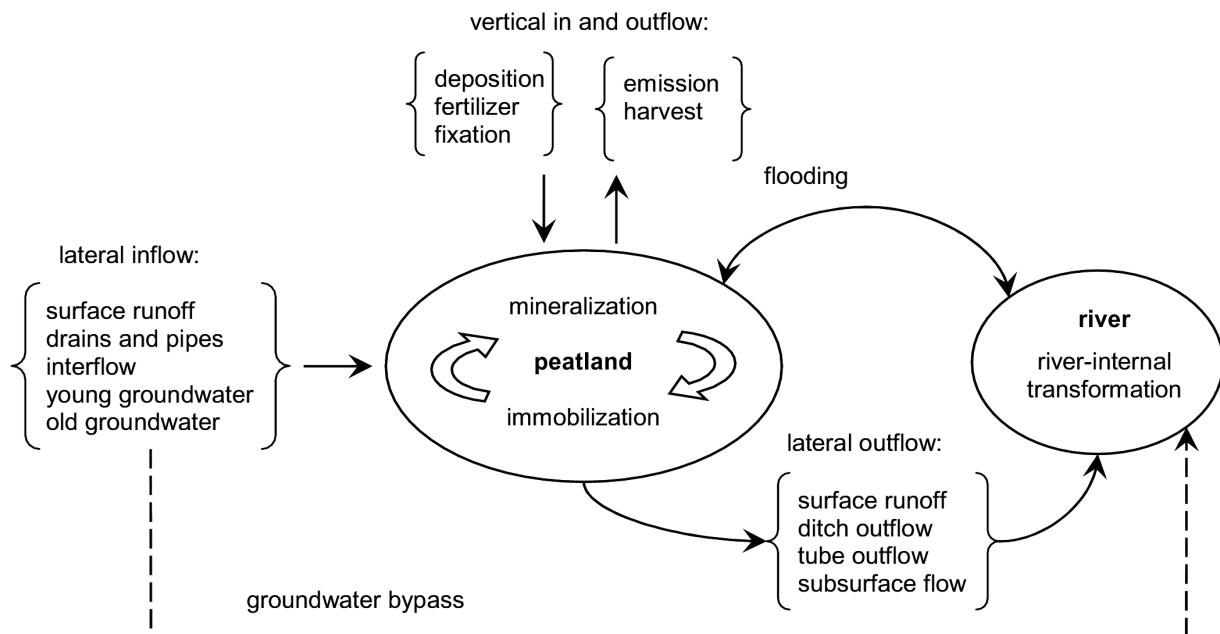


Figure 4.6: Nitrogen balance of a minerotrophic peatland. Adapted from TREPEL & KLUGE (2004).

plots in Europe was approximately $10 \text{ kg N ha}^{-1} \text{ a}^{-1}$, measured for the years 1998 - 2003 (BFH 2006). In Central Europe, N-deposition was mostly higher than in alpine, northern, and southern European regions. On pristine and not fertilized peatlands, N-deposition can influence a peatland sustainably, as it contributes to eutrophication and thus leads to a change in vegetation structure (VAN DOBBEN *et al.* 2006, HAYDEN & ROSS 2005, TREPEL 2000).

Quantitatively, **fertilizer** is the most important source of nitrogen in agricultural used ecosystems. In the state of Schleswig-Holstein, Germany, it is suggested to apply fertilizer in accordance with the expected harvest and other N-sources (LANDWIRTSCHAFTSKAMMER SCHLESWIG-HOLSTEIN 2006). On pastures generally only 45 - 80% of the recommended fertilizer of that of wet meadows is needed (LANDESANSTALT FÜR PFLANZENBAU FORCHHEIM 2005).

N₂-fixation takes place by free-living bacterias (aerobic *Azotobacter* and anaerobic *Clostridium*) as well as mutualistic association between some vascular plants and N-fixing organisms, such as Actinomycetes in partnership with woody plants such as *Myrica gale* and *Alnus* spp., and by Cyanobacteria, often in association with *Sphagnum* (RYDIN & JEGLUM 2006). Especially at nutrient poor sites, N₂-fixation is an important nitrogen source. At grasslands on mineral soils, N₂-fixation by legumes plays an important role as a natural nitrogen source. The following N₂-fixation rates are mentioned in the literature: $70 - 85 \text{ kg N ha}^{-1} \text{ a}^{-1}$ in a wet alder carr, $40 - 45 \text{ kg N ha}^{-1} \text{ a}^{-1}$ in a drained alder forest (DITTERT 1992 in TREPEL 2000), 1% cover of legumes increases fixation by $3 - 5 \text{ kg N ha}^{-1} \text{ a}^{-1}$ (RIEDER 1983 in TREPEL 2000). Thus, in Schleswig-Holstein wet grasslands with a cover of 4 - 7% legumes, N₂-fixation is typically between 15 and $20 \text{ kg N ha}^{-1} \text{ a}^{-1}$ (TREPEL 2000).

N-input with **groundwater and surface water** plays an important role in hydrologically untouched peatlands. Water quality highly influences vegetation in pristine mires. Groundwater input is highly influenced by land use intensity of catchment area. Eutrophication of surface waters leads to eutrophication of peatlands influenced by rivers and lakes. In drained peatlands, water input pathway is disturbed due to missing hydrological contacts. Lateral inflowing groundwater is flowing fast in ditches to the next surface water. Flooding at lakes and rivers occurs only at climatically extreme events due to hydrological changes of surface waters and regulation mechanisms. In most agricultural landscapes for the examination of the nitrogen cycle at the site scale, the inflow is quantitatively not important. Lateral nitrogen inflow is either denitrified when flowing through an anaerobic carbon rich environment or directly transported into the river network when tubes and ditches are present.

Mineralization of organic material in peatlands depends on temperature, pH-value, water table, soil moisture, peat type, vegetation and degradation of peat soil (SCHRAUTZER 2004). Organically bound nitrogen is transformed by microbiological processes into different compounds. The first step is ammonification which occurs under both aerobic and anaerobic conditions. Under aerobic conditions, ammonia (NH_4^+) is oxidized to nitrate (NO_3^-) in several steps. This process is called nitrification. As nitrate is much more mobile than ammonium it is more likely to be leached. An analysis of literature values shows that N-mineralization is increasing with increasing drainage depth (SCHRAUTZER 2004, RENGER *et al.* 2002). At water tables of 0 - 15 cm below surface, $100 \text{ kg N ha}^{-1} \text{ a}^{-1}$ are released within the first 20 cm of the soil profile. On intensive grassland mineralization can reach $600 \text{ kg N ha}^{-1} \text{ a}^{-1}$ (SCHRAUTZER 2004).

RENGER *et al.* (2002) developed regression equations for N-release for four different types of minerotrophic peatlands in northeast Germany, each with land use type grassland. They correspond to the equations of RENGER *et al.* (2002) for the decrease of peat thickness (equation 4.6 on page 18). The N-release by mineralization $NMIN_{Renger}$ [$\text{kg ha}^{-1} \text{ a}^{-1}$] of peatland type a (Erd-fen with peat thickness $\geq 1 \text{ m}$; confer

Table 4.6: Harvest and production parameters in the literature, associated to land use categories and vegetation types of PMDSS (compare table 5.3 on page 60).

Land use category (in PMDSS) ^a	Standing crop pro- duction	relation kg N/ t dry matter	Harvest	N-harvest	N- production standing crop	Biomass N- production
-	t dry matter ha ⁻¹ a ⁻¹	kg N/ t dry matter	t dry matter ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹
1 Arable land (grain)		17 ^g	5.8 ^m	98.6 ^m , 175 ⁿ		
1 Arable land (maize)		3.6 ^g	34.4 ^m	123.8 ^m , 175 ⁿ		
2 Forest, 12 none (forest)	3.5 ^{bc}	20.7 ^h		10 ⁿ		145 ^o
3 Grassl., int. mow.	10 ^{bd}	9-15.7 ^e , 22 ^k , 22-28 ⁱ	7 ^k , 7-10 ^l , 7.5-11 ⁱ	155 ^k , 165 ⁿ , 165-305 ⁱ	33-210 ^e	
4 Grassl., int. mow.+past.	10 ^{bd}	9-15.7 ^e	7-10 ^l	125 ⁿ	33-210 ^e	
5 Grassl., int. past.	10 ^{bd}	9-15.7 ^e		20 ⁿ	33-210 ^e	
6 Grassl., mod. mow.	5 ^{be}	17.3-17.5 ^e , 16 ⁱ , 18 ^k	5.5 ^k , 6 ⁱ , 5.5-6.5 ^l	90 ⁿ , 95 ⁱ , 100 ^k	80, 88 ^e	
7 Grassl., mod. mow.+past.	5 ^{be}	17.3-17.5 ^e	5.5-6.5 ^l	60 ⁿ	80, 88 ^e	
8 Grassl., mod. past.	5 ^{be}	17.3-17.5 ^e		10 ⁿ	80, 88 ^e	
9 Nature conservation m.	3.5 ^{be}	13 ⁱ , 14.2-15.8 ^e	2.5 ^k , 3-3.5 ^l , 4 ^{ml}	50 ^{ml}	43-67 ^e	
10 Short abandon. sp. rich	7 ^{bef}	18.7, 22.5 ^{ef}	7 ^{lf}		92 ^{ef}	
11 Short abandon. sp. poor	7 ^{bef}	18.7, 22.5 ^{ef}	7 ^{lf}		92 ^{ef}	
12 None (reed)	10 ^{be}	9.2 ^e	14 ^k		143, 149 ^e	

^aLand use categories at length in table 5.3 on page 60

^bUsed as standard value in vegetation module (chapter 4.3.3 on page 23)

^cDILLY *et al.* (2000)

^dOLFF & BAKKER (1991)

^eTREPEL (2000)

^fValues of tall sedges

^gCalculated from other columns

^hCalculated from other columns, with assumption that biomass production is twice standing crop production (DILLY *et al.* 2000)

ⁱLANDESANSTALT FÜR PFLANZENBAU FORCHHEIM (2005)

^kDIERSCHKE & BRIEMLE (2002)

^lLANDWIRTSCHAFTSKAMMER SCHLESWIG-HOLSTEIN (2006)

^mLANDESAMT FÜR VERBRAUCHERSCHUTZ UND LANDWIRTSCHAFT FRANKFURT(ODER) (2002)

ⁿUsed in expert system WETTRANS (TREPEL *et al.* 2004)

^oWIEBE (1998)

explanation to equation 4.6) is calculated as follows:

$$NMIN_{Renger} = 3.58 \cdot SWT - 0.0135 \cdot SWT^2 + 20.7 \quad (4.21)$$

where SWT = mean summer water table [cm below surface]. Further explanation is given in chapter 4.3.1.1 on page 16.

Nitrogen leaches with seepage water mainly in form of nitrate, ammonia, and organic N. Measured leaching of anorganic N on sites ranges between 0 and 60 kg N ha⁻¹ a⁻¹ (TREPEL 2000). Maximum measured anorganic nitrogen leaching values on peatlands of 200 to 300 kg N ha⁻¹ a⁻¹ were determined with lysimeter investigations, where maize was growing (BEHRENDT *et al.* 1996, 1994 in TREPEL 2000). On catchment scale beside anorganic N (8.9 to 29.6 kg N ha⁻¹ a⁻¹) also total N (15 to 99.4 kg N ha⁻¹ a⁻¹) have been measured on semi-natural peatlands (DEVITO *et al.* 1989 in TREPEL 2000). This suggests that organic N in seepage can reach up to twice or three times as much nitrogen as anorganic N. Usually shortly after rewetting by flooding, a higher amount of nitrogen discharge can be observed (HÖHNE 2000 in SCHWILL 2003).

An important process under anaerobic conditions is microbial **denitrification**. In this process, nitrate (NO₃⁻) or nitrite (NO₂⁻) is reduced in several steps to elementary nitrogen (N₂). One intermediate product is the greenhouse gas N₂O. In agricultural vegetation types, denitrification is - next to harvest - the most important output pathway. Annual denitrification rate on peatlands correlates positively to nitrogen input, nitrification, and depth to groundwater table (TREPEL *et al.* 2000). Potential loss of nitrogen on peatlands due to denitrification can reach up to 150 - 300 kg N ha⁻¹ a⁻¹ (SCHRAUTZER 2004). For wetlands in general in the temperate zone the maximum potential rate of nitrogen removal ranges even from 1000 to 3000 kg N ha⁻¹ a⁻¹ (VERHOEVEN *et al.* 2006). Beside denitrification, N₂O can also develop as a side-product of nitrification. In the literature, a range of values of N₂O-emission between 0 and 14 kg N ha⁻¹ a⁻¹ is given (SCHRAUTZER 2004). High N₂O-emission rates are found especially on drained peatlands. The higher the denitrification rate is, the higher also the N₂O-emission. In addition it can be assumed that N₂O-emission is higher at fluctuating water tables (SCHRAUTZER 2004, REGINA *et al.* 1999).

The amount of NO₃-discharge and denitrification is mainly dependent on the summer water table in relation to peat thickness (MERZ *et al.* 2005, HEFTING *et al.* 2004, ANTONY & REINERT 2003). If the groundwater table stays within the peat layer, NO₃-discharge is low. At groundwater tables close to the border between peat layer and underlying permeable layer, NO₃-discharge is increasing.

Immobilization is the fixation of nitrogen in organic material. Apart from atmospheric N-fixation, plants take up nitrogen from soil water in the form of nitrate and ammonia via roots. At low pH values and anoxic conditions, availability of nitrate is much lower than that of ammonia. A part of immobilized nitrogen in plants can be removed by **harvest** from the site. In table 4.6, literature values for harvest and biomass production parameters are summarized. Standing crop is the living above ground biomass of plants. Production (more precisely primary production) is the rate with which plants produce biomass (TOWNSEND *et al.* 2003). The proportion of harvested standing crop is dependent on land use types. On meadows, standing crop production is roughly the amount of harvest. The N-content in the whole biomass produced is important to account for immobilized nitrogen. In meadow communities the relationship of aboveground to belowground biomass is in average 3:1 to 2:1. In small sedge meadows the relation can reach up to 1:6 to 1:9 (TREPEL 2000). On the dry site of alder forest, a relation of 1:1 was measured (DILLY *et al.* 2000).

4.3.5.2 Module description

The PMDSS nitrogen module was developed on the basis of the state of knowledge (summarized in the last chapter) and will be described in the following paragraphs.

The nitrogen balance is calculated in worksheet *Mod_N*. Relevant outputs for PMDSS of this module are nitrogen discharge, N₂O-emission, and harvest of plants.

The 'Nitrogen balance of the site' is calculated in PMDSS with:

$$NDEP + NFIX + NFER + NMIN = NPRO + NDIS + NDE + NE \quad (4.22)$$

where *NDEP* = nitrogen deposition, *NFIX* = nitrogen fixation, *NFER* = nitrogen fertilizer, *NMIN* = nitrogen mineralization, *NPRO* = nitrogen content in biomass (production), *NDIS* = nitrogen discharge, *NDE* = N₂O-emission, and *NE* = N₂-emission. The unit of all components is kg N ha⁻¹ a⁻¹. At the site scale, most lateral nitrogen inflow is either denitrified when flowing through an anaerobic carbon rich environment or directly transported into the river network when tubes and ditches are present. Thus, inflow pathways by groundwater and surface water are neglected (figure 4.6 on page 33). Also, flooding is neglected as an input pathway. As PMDSS applies for eutrophic minerotrophic peatlands, it is assumed that there is always enough total N available, so that N reserves and their changes are not calculated. Nitrogen discharge is the amount of nitrogen in the lateral water outflow of the peatland site. Depending on the selected peatland site, nitrogen discharge in PMDSS can be the outflow to the river or other surface waters, but also to the neighbouring peatland site (figure 4.1 on page 12).

The nitrogen content in biomass is separated, as follows:

$$NPRO = NHAR + NIMM \quad (4.23)$$

where *NHAR* = nitrogen content in harvested biomass and *NIMM* = immobilized nitrogen. The unit of all components is kg N ha⁻¹ a⁻¹.

4.3.5.2.1 Nitrogen input

Nitrogen of the inflow pathways is summarized as nitrogen input *NINP* [kg N ha⁻¹ a⁻¹]:

$$NINP = NDEP + NFIX + NFER + NMIN \quad (4.24)$$

Deposition of nitrogen *NDEP* is an input parameter and is the sum of dry and wet deposition. The default value for *NDEP* [kg N ha⁻¹ a⁻¹] is calculated with

$$NDEP = NC \cdot PRE / 100 \cdot 2 \quad (4.25)$$

where *NC* = nitrogen concentration in precipitation [mg/ l] and *PRE* = precipitation [mm]. In PMDSS, the default value for *NC* is set to 1.7 mg N/ l, which is the mean concentration of N in precipitation in Schleswig-Holstein, northern Germany (TREPPEL & KLUGE 2004).

Fixation of nitrogen *NFIX* is depending on the vegetation type, calculated in the vegetation module (chapter 4.3.3). If the vegetation type is not alder forest, the maximum value is set to 17 kg N ha⁻¹ a⁻¹, in accordance to typical values of wet grassland with legumes (chapter 4.3.5.1).

N- Fertilizer *NFER* is an input parameter. Default values in PMDSS are depending on the land use categories (table 5.5) and were adopted from the expert system WETTRANS (TREPPEL *et al.*

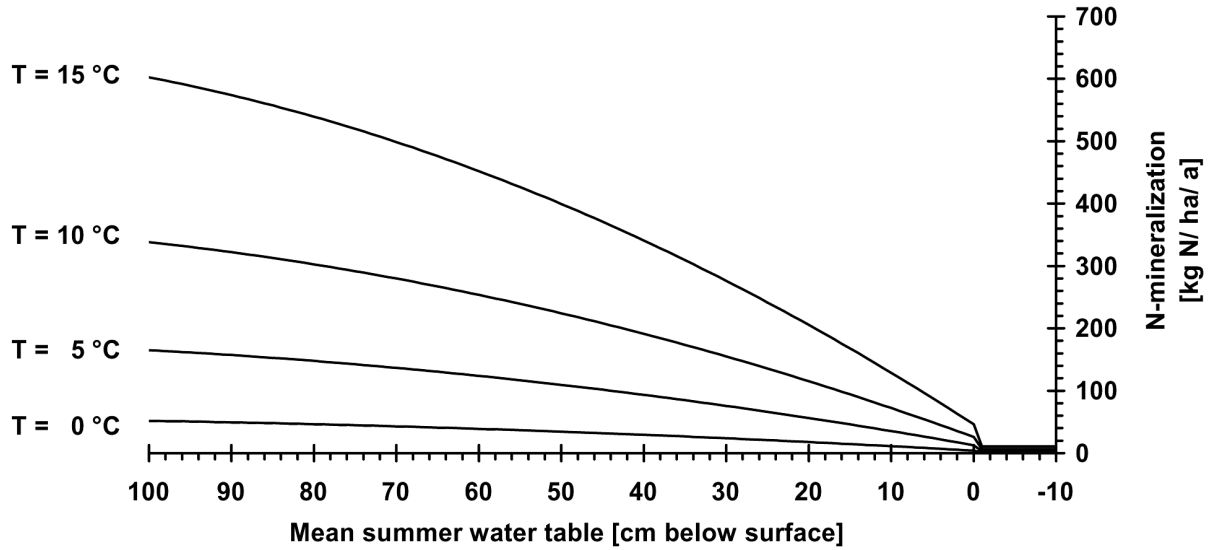


Figure 4.7: Example of how nitrogen mineralization is calculated, depending on mean summer water table and air temperature for land use categories 2 - 12. Extended equation from RENGER *et al.* (2002).

2004). They are oriented on recommendation values for farmers in Schleswig-Holstein/ Germany (LANDWIRTSCHAFTSKAMMER SCHLESWIG-HOLSTEIN 2006).

For calculation of **nitrogen mineralization** $NMIN$, equation 4.21 was extended with the same factors as subsidence rate (equation 4.7 on page 19): temperature factor, subsidence factor, and land use factor. Additionally, the mean summer water table is reduced by mineral layers above the mean summer water table and below the peat and reduced by the half clay layer within the peat. The equation is valid for the sites, which were already drained for several years.

By default, $NMIN$ [$\text{kg N ha}^{-1} \text{ a}^{-1}$] is calculated at mean summer water tables ≥ 1 cm below surface with

$$NMIN = \left(3.85 \cdot \left(PTaw + \frac{Cl}{2} \right) - 0.0135 \cdot \left(PTaw + \frac{Cl}{2} \right)^2 + 20.7 \right) \cdot TF \cdot SF \cdot LUF \quad (4.26)$$

where $PTaw$ = peat thickness above the summer water table [cm] (equations 4.8 - 4.11 on page 19), Cl = clay layer thickness near surface [cm], TF = temperature factor (equation 4.12 on page 19), SF = subsidence factor and LUF = land use factor. Thus, N-mineralization is rising with increasing depth to mean summer water table and increasing air temperatures (figure 4.7). Factors are described in detail in chapter 4.3.1.2 on page 18.

At mean summer water tables < 1 cm below surface, $NMIN$ is set to $5 \text{ kg N ha}^{-1} \text{ a}^{-1}$.

Furthermore, the user can choose to use an alternative equation from worksheet *Mod_Adj* (a new equation, inserted by the user).

4.3.5.2.2 Nitrogen content in biomass and harvest

In PMDSS, nitrogen uptake by plants is only limited by available nitrogen and depends on typical complete biomass production for different land use types. Available nitrogen for biomass production $NAVA$ [$\text{kg N ha}^{-1} \text{ a}^{-1}$] is increasing with increasing nitrogen input and increasing depth to summer water table (TREPPEL, pers. comm.):

$$NAVA = NINP \cdot (-0.5 \cdot SWT/100 + 1) \quad (4.27)$$

Table 4.7: Typical harvest and connected parameters in PMDSS.

Land use category ^a	Harvested proportion of standing crop production	Typical standing crop production	<i>conv</i> ^b	Typical harvest	Typical N-harvest	Typical N-production standing crop	Typical biomass production	Typical biomass N-production
-	0 to 1	t dry matter ha ⁻¹ a ⁻¹	kg N/ t dry matter	t dry matter ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹	t dry matter ha ⁻¹ a ⁻¹	kg N ha ⁻¹ a ⁻¹
1 Arable land (grain)	0.95	6.3	17	6	102	107	9	161
1 Arable land (maize)	0.95	36	3.6	34.2	123	130	54	194
2 Forest, 12 none (forest)	0.5	8	15	4	60	120	12	180
3 Grassl., int. mow.	0.8	10	15	8	120	150	15	225
4 Grassl., int. mow.+past.	0.7	10	15	7	105	150	15	225
5 Grassl., int. past.	0.15	10	15	1.5	23	150	15	225
6 Grassl., mod. mow.	0.8	5	15	4	60	75	8	113
7 Grassl., mod. mow.+past.	0.7	5	15	3.5	53	75	8	113
8 Grassl., mod. past.	0.15	5	15	0.8	11	75	8	113
9 Nature conservation m.	0.7	3.5	15	2.5	37	53	5	79
10 Short abandon. sp. rich	0	7	15	0	0	105	11	158
11 Short abandon. sp. poor	0	7	15	0	0	105	11	158
12 None (reed)	0	10	15	0	0	150	15	225

^aLand use categories at length in table 5.3 on page 60

^b*conv* is the conversion factor of t dry matter into kg N

At a depth to mean summer water tables lower than 1 cm applies

$$NAVA = NINP \cdot 0.9 \quad (4.28)$$

This implies that plants are growing higher with higher water tables.

Nitrogen content in the biomass production *NPRO* is calculated with

$$NPRO = \min(NPRO_{pot}; NAVA) \quad (4.29)$$

where *NPRO_{pot}* = potential N-content in biomass production [kg N ha⁻¹ a⁻¹], and *SWT* = mean summer water table [cm below surface].

The potential N-content in biomass production is derived from calculations of the vegetation module:

$$NPRO_{pot} = SCPRO \cdot 1.5 \cdot conv \quad (4.30)$$

where *SCPRO* is the potential standing crop production [t dry matter ha⁻¹ a⁻¹], calculated in the vegetation module (chapter 4.3.3.3 on page 26). Factor 1.5 accounts for the relationship between standing crop production and whole biomass production. The conversion factor *conv* [kg N/ t dry matter] is usually set to 15 (for grain: 17; maize: 3.6) and accounts for conversion of biomass production into nitrogen production. In order to get smooth transitions, average values were taken for those factors instead of distinguishing different vegetation types.

Depending on the land use category, part of the nitrogen in the biomass *NPRO* is removed from the site with **harvest**. The remaining part is treated as immobilized nitrogen *NIMM* (equation 4.23).

Table 4.8: Factor fn for the partitioning function of $DIFF$ into $NDIS$, NE , and NDE .

ANAER (Anaerobic peat layer) ^a m	NDIS (N-discharge) kg N ha ⁻¹ a ⁻¹	NE (N ₂ -emission) kg N ha ⁻¹ a ⁻¹	NDE (N ₂ O-emission) kg N ha ⁻¹ a ⁻¹
> 0.5	$0.05 + BIO^b \cdot 0.01$	$1 - NDIS - NDE$	$SWT\ fl^c \cdot 0.0025$
-0.3 to 0.5	0.8	0.1	0.1
< -0.3	0.9	0.075	0.025

^aANAER = anaerobic peat layer, which is the difference between peat thickness and mean summer water table

^bBIO = dying biomass after rewetting [t dry matter ha⁻¹ a⁻¹]

^cSWT fl = water table fluctuations (standard deviation of summer water table) cm

The harvest [t dry matter ha⁻¹ a⁻¹] is calculated with

$$HAR = PH \cdot NPRO / 1.5 / conv \quad (4.31)$$

where PH is the proportion of harvest of standing crop production, depending on the land use category (table 5.5 on page 64) and $NPRO$ is the nitrogen content in biomass (equation 4.29). The parameter PH can be adjusted by the user if necessary in worksheet *Input_Tab*. Parameters were adjusted to get similar values for typical harvest and connected parameters in PMDSS (table 4.7) as reported in the literature (table 4.6). Typical standing crop production values are the initial values of standard vegetation types used in the vegetation module.

4.3.5.2.3 Nitrogen discharge and N₂O-emission

To begin with, the uptake of nitrogen by plants is calculated from the nitrogen input $NINP$. Then, the remaining nitrogen is either denitrified or leached with groundwater or surface water. Concerning denitrification, only the gases N₂O and N₂ are distinguished as only N₂O is of interest in PMDSS.

The nitrogen content in biomass production is subtracted from the nitrogen input. This **difference** $DIFF$ is calculated with

$$DIFF = NINP - NPRO \quad (4.32)$$

and is distributed to the three output pathways: N-discharge ($NDIS$), N₂O-emission (NDE), and N₂-emission (NE). The partitioning is mainly dependent on the mean summer water table in relation to peat thickness, but also on dying biomass which occurs usually shortly after rewetting by flooding, and on water table fluctuations.

The three output values are calculated with

$$NDE = DIFF \cdot fn \quad (4.33)$$

$$NE = DIFF \cdot fn \quad (4.34)$$

$$NDIS = DIFF \cdot fn \quad (4.35)$$

where fn is a dimensionless factor taken from table 4.8. If there is an impermeable layer below the peat layer, the factors for $ANAER > 0.5$ m are always used in the model. The determination of factor fn is based

on the state of knowledge (page 36, TREPEL, pers. comm.). As nitrogen input is increasing with increasing depth to mean summer water table, N-discharge and N₂O-emission are also increasing in this case. If there is a permeable layer below the peat layer, N-discharge and N₂O-emission are higher if the mean summer water table is near the layer change or below it. At mean summer water tables within the peat layer, N-discharge is influenced by nitrogen of dying biomass after rewetting *BIO*. N₂O-emission increases with increasing water table fluctuations.

4.3.6 Global Warming Potential

4.3.6.1 State of knowledge

The Global Warming Potential (GWP) is an index to estimate the potential future impact of the emission of different greenhouse gases upon the climate system (IPCC 2001). The GWP has been defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas which is usually CO₂. Thus, the GWP expresses the integrated forcing of a pulse and not a constant emission over a chosen time horizon (discussed in detail by FROLKING *et al.* 2006). Radiative properties control the absorption of radiation per kilogramme of gas present at any instant, but the lifetime controls how long an emitted kilogramme is retained in the atmosphere and hence is able to influence the thermal budget. The atmospheric lifetimes of the greenhouse gases CH₄ and N₂O are generally shorter than that of CO₂. The lifetime of CO₂ varies between 3.4 and 10⁸ years (JOOS *et al.* 1996 in FROLKING *et al.* 2006). Thus GWPs of CH₄ and N₂O are basically decreasing with an increasing time horizon.

In table 4.10, typical greenhouse gas emission rates of peatlands found in the literature are summarized and corresponding GWPs were calculated with factors of IPCC (2001) (table 4.9). High value ranges demonstrate the high variability between peatlands and uncertainties about radiative forcing of peatlands. The GWP of peatlands is mainly positive, meaning they are contributing to climate warming. On wet (pristine, restored, rewetted) peatlands, the GWP is decreasing with an increasing time horizon due to the high CH₄-emission. In some cases, those peatlands contribute to the reduction of the global warming effect (at high CO₂-sequestration and low CH₄-emission rates). At drained sites, the difference of the GWP between time horizons is much smaller due to negligible CH₄- and low N₂O-emission rates. If the GWP is higher at wet or at drained sites differs also with the time horizon. Short term GWP (20 year horizon) of pristine peatlands can get greater than that of drained peatlands. Mid-term GWP (100 year horizon) of wet peatlands tend to be lower than that of drained peatlands. Long-term GWP (500 year horizon) is generally lower at wet sites. Furthermore, GWP is increasing with increasing drainage depth on drained sites and is therefore highest at arable land.

The GWP method is discussed in the literature (FROLKING *et al.* 2006). With a dynamic approach, FROLKING *et al.* 2006 are showing, that the impact of a change in CH₄ emission dominates the radiative forcing impact in the first few decades and the impact of the change in CO₂ emission slowly exerts its influence. This tendency is also indicated by regarding the GWP of the three time horizons.

Generally, the GWP for the 100 year horizon and the factors given in IPCC (1996) are used, as this is the basis for UNFCCC reporting. In difference to IPCC (1996), the recalculated GWP factors in IPCC (2001) are higher for methane and lower for N₂O (table 4.9).

4.3.6.2 Module description

The GWP is calculated in worksheet *Mod_GWP*. The PMDSS GWP module was developed on the basis of the state of knowledge (summarized in the last chapter) and will be described in the following paragraphs.

In PMDSS, the GWP [kg CO₂-C-equ. ha⁻¹ a⁻¹] is calculated for three different time horizons *h* (20, 100, and 500 years) with

$$GWP_h = CO2_C + f_{g_h} \cdot CH4_C + f_{g_h} \cdot NDE \quad (4.36)$$

where *CO2_C* = CO₂-emission [kg C ha⁻¹ a⁻¹], *CH4_C* = CH₄-emission [kg C ha⁻¹ a⁻¹], *NDE* = N₂O-emissions [kg N ha⁻¹ a⁻¹] and *f_{g_h}* the GWP factor of each gas, converted to 1 kg C and N respectively,

Table 4.9: The atmospheric lifetime and Global Warming Potentials over different time horizons of radiatively important gases (IPCC 2001), also converted to 1 kg C and N respectively.

Gas	Atmospheric lifetime [years]	Global Warming Potential factor [kg CO ₂ -equ.] and [kg CO ₂ -C-equ.] respectively for the time horizons		
		20 years	100 years	500 years
		CO ₂ [1 kg CO ₂]	variable	1
CH ₄ [1 kg CH ₄]	12	62	23	7
N ₂ O [1 kg N ₂ O]	114	275	296	156
CO ₂ [1 kg CO ₂ -C]		1	1	1
CH ₄ [1 kg CH ₄ -C]		22.5	8.4	2.5
N ₂ O [1 kg N ₂ O-N]		118	127	67

Table 4.10: Summarized greenhouse gas emission rates in the literature for minerotrophic peatlands (median values and range). GWPs are calculated as in PMDSS (chapter 4.3.6.2, table 4.9). The sources of the emission intervals given in this table are partly overlapping.

Parameter Unit	CO ₂ kg C ha ⁻¹ a ⁻¹	CH ₄ kg C ha ⁻¹ a ⁻¹	N ₂ O kg N ha ⁻¹ a ⁻¹	GWP ₂₀ ^a	GWP ₁₀₀ ^a kg CO ₂ -C equ. ha ⁻¹ a ⁻¹	GWP ₅₀₀ ^a
Northeast Germany (AUGUSTIN 2001)						
- rewetted/ponded	-2250 to -140 ^b	2.7 to 521	0.0 to 0.8	-2200 ^c to 11700	-2200 ^c to 4300	-2200 ^c to 1200
- drained	2900 to 6700	-1.4 ^b to 3.3	0.3 to 26.9	2900 to 9900	2900 to 10100	2900 to 8500
Europe (MEYER <i>et al.</i> 2001) ^d						
- pristine (ponded/permanent wet)	-480 to -140 ^b	190 to 497	-0.2 ^b to 0.8	3800 to 11100	1100 to 4100	0 to 1200
- partly drained (depth to water table approx. 30 cm)	3849 to 4787	-1.3 ^b to 18.3	0.1 to 11.4	3800 to 6600	3900 to 6500	3900 to 5600
- drained (depth to water table > 50 cm)	4120 to 6700	-1.3 ^b , to 3.3	0.3 to 5.1	4100 to 7400	4100 to 7400	4100 to 7100
Europe (BYRNE <i>et al.</i> 2004) ^e						
- pristine	-440 ^b (-530 to -210)	131 (60 to 150)	0.05 (-0.01 to 0.112)	2500 (820 to 3200)	670 (-27 to 1100)	-110 ^c (-380 to 170)
- restoration	-	12.4 (6.5 to 18.3)	0.64	350 ^f (220 to 490)	190 ^f (140 to 240)	74 ^f (59 to 89)
- forest (drained)	-200 ^b (-210 to 480)	-0.05 ^b (-1.8 to 44.5)	1.83 (0.09 to 26.9)	15 (-240 to 4700)	32 (-210 to 4300)	-78 ^c (-210 to 2400)
- drainage (for forest)	400 (140 to 3600)	1.0 (0 to 11.3)	1.05 (0.08 to 2.23)	550 (150 to 4100)	540 (150 to 4000)	470 (150 to 3800)
- grassland	4120 (820 to 6580)	0.4 (-1.04 to 105)	5.05 (0.30 to 38.8)	4700 (830 to 13500)	4800 (850 to 12400)	4500 (840 to 9400)
- arable	4090 (1090 to 10600)	-0.2	11.61 (4.0 to 56.4)	5500 (1600 to 17300)	5600 (1600 to 17800)	4900 (1400 to 14400)
Worldwide (JOOSTEN & CLARKE 2002) ^g						
- pristine	-250 ^b	297	0.1	6400	2300	500
- drained (grassland)	3465 (1910 to 6580)	0 (-1.4 to 5)	5.7 (0.6 to 16)	4100 (1900 to 8600)	4200 (2000 to 8700)	3800 (1900 to 7700)

^aGWP=Global Warming Potential for time horizons 20, 100 and 500 years respectively. Values are rounded.

^bNegative values account for netto sequestration of greenhouse gases

^cNegative values mean that the peatland contributes to a reduction of the global warming effect

^dBased on emission measurements on minerotrophic peatlands in northern Germany and literature values of Europe

^eLiterature review

^fGWP without CO₂-C

^gMeasurements and estimations from the literature (Globally, USA, Sweden, Finland, England, Germany, Canada, The Netherlands)

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dependent on the time horizon (table 4.9). The GWPs in the model represent the trends described in the last chapter and given in table 4.10.

4.3.7 Hydrology

4.3.7.1 State of knowledge

A generalized water balance equation for peatlands can be written as follows:

$$\Delta V / \Delta t = qP + qSWI + qSSWI - qET - qSWO - qSSWO \pm qGWS \pm qFEX$$

where $\Delta V / \Delta t$ = change in storage per unit time, qP = precipitation, $qSWI$ = surface water inflow (surface runoff, ditch inflow, well inflow), $qSSWI$ = subsurface water inflow (interflow, drains and pipes, near-surface groundwater), qET = evapotranspiration, $qSWO$ = surface water outflow (surface runoff, ditch outflow), $qSSWO$ = subsurface water outflow (tube flow, subsurface outflow), $qGWS$ = groundwater seepage (upward and downward) and $qFEX$ = flood exchange (compare figure 4.8). All units are in volume per unit time. The magnitude of the various terms varies with peatland type. Bogs receive water only through precipitation, whereas in fens inflow with surface water and groundwater are dominant. In difference to pristine mires, the water exchange pattern in drained peatlands includes other lateral inflow pathways, such as drains and pipes from neighbouring fields and lateral outflow pathways through ditches and tubes. Via the different inflow and outflow pathways, peatlands are connected with their surrounding catchment. (RYDIN & JEGLUM 2006, TREPEL & KLUGE 2004, EDM 2001, HEATHWAITE 1995)

'Storage' is the total volume of water contained in a peatland. Change in storage is reflected by a rise or fall in water table. The amount of water from different inflowing water sources is dependent on the landscape position of the peatland and morphological and geohydrological features of the surrounding basin. The flow pattern inside the peatland is mainly controlled by the thickness and physical parameters of the peat layer, the occurrence of underlying aquifers, the occurrence of impermeable intercalated layers such as clay, silt, or gytja and different drainage measures. (TREPEL & KLUGE 2004:359)

The water storage of pristine mires and drained peatlands differ considerably. Water surplus is essential for the growing of mires. In pristine mires, the water tables are usually near the surface and the water content

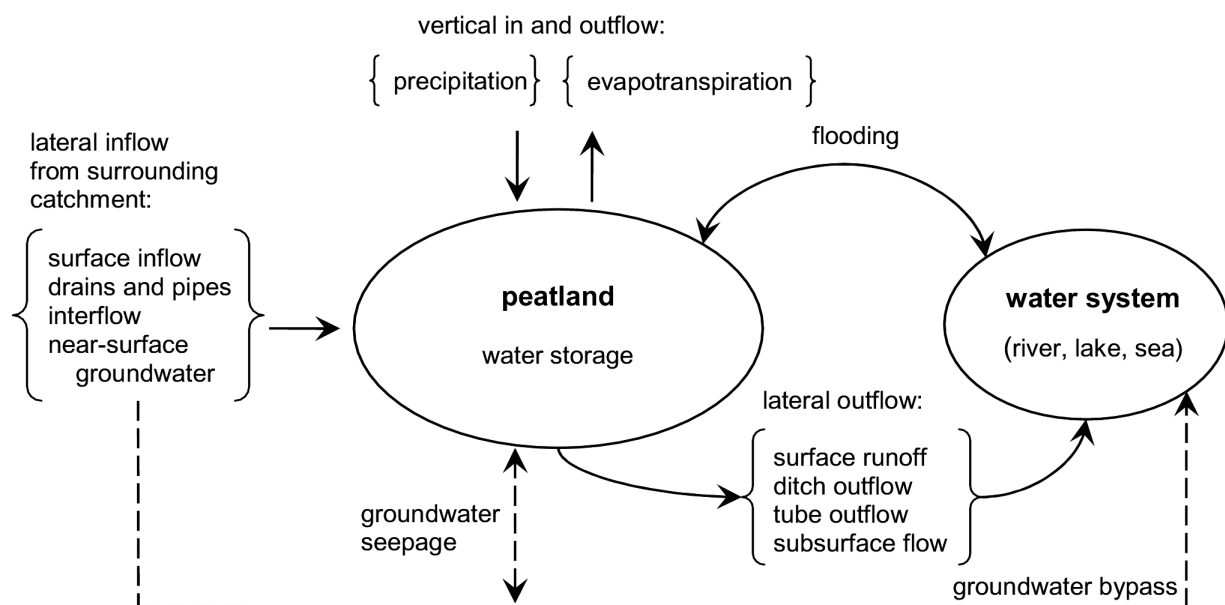


Figure 4.8: Water balance of minerotrophic peatlands. Adapted from TREPEL & KLUGE (2004).

is between 95 and 70 volume % (EGGELSMANN 1990). For bogs, a concept was developed where a peatland consists of two layers: (1) the acrotelm, a periodically anaerobic layer and (2) the katotelm, a constantly water saturated layer (INGRAM 1983). This concept is transferred to fens by several authors (EDOM 2001). Physical properties are changing with depth. In the acrotelm, porosity and thus saturated conductivity is generally higher in comparison to the katotelm and is decreasing with depth.

The drainage of peatlands leads to a decrease in water storage and to substantial changes of both the physical properties and the structure of the peat layer, especially in the aerobic horizons. As subsidence includes the processes shrinkage, compression, and mineralization, pore volume is decreasing mainly in the aerobic peat layer. This is connected with a change in pore size distribution (increase in macro pores and fine pores) and a decrease of hydraulic conductivity, water repellency, and water storage capacity. The saturated hydraulic conductivity is higher in the permanent anaerobic peat layers. The higher bulk density in the aerobic peat layers causes a general increase in water table fluctuations.

Some mires and drained peatlands have the ability to change the peat surface depending on the water table (mire breathing) (STEGMANN *et al.* 2001). Thus, some peatlands are able to adapt the surface level to a change in water storage.

On an annual basis, water table changes are usually small, except where climatological conditions are extreme (e.g. droughts) or where human interventions modify the natural water balance of the peatland (HEATHWAITE 1995). Water tables are changing seasonally in pristine mires as well as in drained peatlands. Water tables are usually lower during the vegetation period (due to higher evapotranspiration rates).

Rewetting peatlands after drainage is complicated due to the changed soil physical properties as well as the changed hydrological conditions in the catchment (SCHOPP-GUTH 1999, KRATZ & PFADENHAUER 2001). Thus, in some cases rewetting might be impossible.

4.3.7.2 Module description

The PMDSS hydrology module was developed in close cooperation with Winfrid Kluge and will be described in the following paragraphs. The mean summer water table is calculated in the worksheets *Mod_Hydro1* and *Mod_Hydro2*. To use this module the value for the parameter 'Use of Hydrology module' in the worksheet *Input_Par* has to be set to 1.

In the hydrology module, the long-term trend of the mean summer water tables is calculated with simple model concepts which consider climatic influences, land use, the connection of the peatland to the catchment, and water bodies as well as properties of the soil profile. Easy quasi stationary model concepts are provided by analytical solutions. In difference to complex dynamical models, easy quasi stationary models are mainly dependent on surrounding water tables and vertical recharge in the wetland.

The mean summer water table of the site is calculated depending on the geometry of the hydrological sector, the surrounding summer water tables, the soil profile, the mean climatic water balance of summer, and the groundwater seepage.

Geometry of hydrological sector

The geometry of the hydrological sector is distinguished into 3 types: quadrangle, parallel flow, and circle (figure 4.9). The investigated site lies within the hydrological sector or might be the same. The hydrological sector is an area with defined hydrological boundary conditions (surrounding summer water tables). The boundaries a, b, c, and d are hydrological features (such as ditches, rivers or a boundary with a certain groundwater level).

The quadrangle might for instance be a situation where at the boundaries a and b are ditches, at boundary

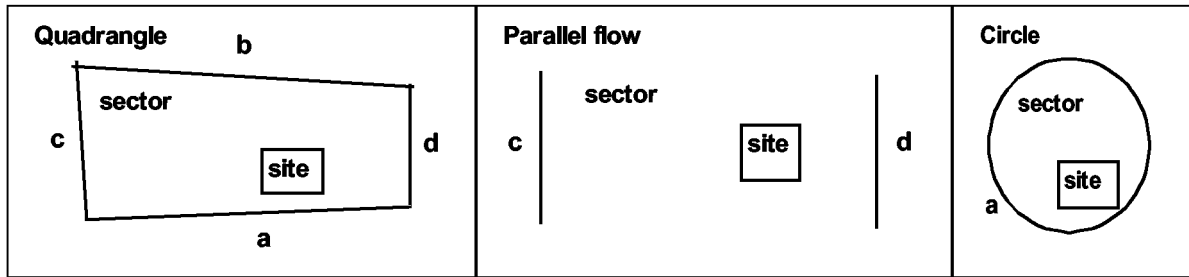


Figure 4.9: Types of hydrological sectors as used in PMDSS. The boundaries a, b, c, and d are hydrological features (such as ditches, rivers or a boundary with a certain groundwater level).

d is a river and boundary c is a bit higher with ground water flow to the sector. The parallel flow might be the same without ditches. The circle might be an ombrotrophic peatland with surrounding summer water tables at the same level.

Soil profile of hydrological sector

From the 2 or 3 soil layers, the mean saturated hydraulic conductivity $ksat$ [m/ a] for the permeable soil profile is calculated with

$$ksat = \frac{ksat_1 \cdot M_1 + ksat_2 \cdot M_2 + ksat_3 \cdot M_3}{M_1 + M_2 + M_3} \cdot 365 \quad (4.37)$$

where $ksat_1$ = saturated hydraulic conductivity of soil layer 1 [m/ d], M_1 = thickness of soil layer 1 [m] and the others analogical. Only layers which are not impermeable are regarded in this calculation (well, semi-, and low permeable layers).

General assumptions

In all three cases the first step is to calculate a theoretical water table of the sector centre HC_0 without net recharge which depends only on the surrounding summer water tables, without any vertical water in- or outflow. This is a geometrical solution (line or area spanned between the surrounding summer water tables).

In a second step, the groundwater mound of the sector centre HC_m due to vertical water inflow is calculated. The assumption is a steady state shallow unconfined groundwater flow. The equations for the calculation of HC_m are based on the analytical solution of the Poisson equation with assumed uniform water tables at the border of the sector (STRACK 1989):

$$\frac{\partial^2 \Phi}{\partial^2 x} + \frac{\partial^2 \Phi}{\partial^2 y} = -N \quad (4.38)$$

where N = net recharge rate [m^3/ a] and Φ = geohydraulic potential.

To account for lateral inflow in PMDSS the net recharge rate N is calculated with

$$N = qGWS + qCWB \quad (4.39)$$

where $qGWS$ = groundwater seepage [m^3/ a] and $qCWB$ = climatic water balance [m^3/ a] in summer.

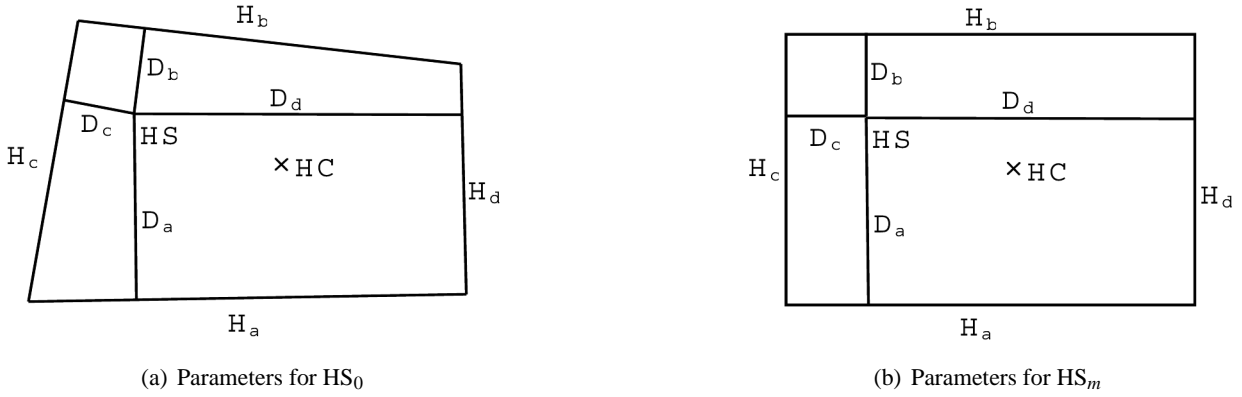


Figure 4.10: Quadrangle and rectangle for calculation of HS_0 (theoretical water table without net recharge of site centre) and HS_m (groundwater mound of the mean summer water table of the site centre).

$$qCWB = qP - qET \quad (4.40)$$

where qP = precipitation [m^3/a] and qET = evapotranspiration [m^3/a] in summer. In PMDSS, the unit m/a is used instead of m^3/a for calculation of the groundwater seepage $qGWS$ and the climatic water balance $qCWB$.

For all 3 geometries, the mean summer water table of the site centre HS [m ASL] is calculated by the superposition of two terms:

$$HS = HS_0 + HS_m \quad (4.41)$$

where HS_0 = theoretical water table without net recharge at site centre [m ASL] and HS_m = groundwater mound of the summer water table at site centre [m].

Quadrangle

The theoretical water table without net recharge of sector centre HC_0 [m ASL] is calculated with

$$HC_0 = \frac{H_a \cdot L_a + H_b \cdot L_b + H_c \cdot L_c + H_d \cdot L_d}{L_a + L_b + L_c + L_d} \quad (4.42)$$

where H_a = the mean summer water table at boundary a [m ASL], L_a = Length of boundary a [m] and the others analogical.

The theoretical water table without net recharge of the site centre HS_0 [m ASL] is calculated with

$$HS_0 = \frac{H_a/D_a + H_b/D_b + H_c/D_c + H_d/D_d}{D_a^{-1} + D_b^{-1} + D_c^{-1} + D_d^{-1}} \quad (4.43)$$

where D_a = the distance of the site centre to boundary a [m] and the others analogical (figure 4.10a).

For the calculation of the groundwater mound of the mean summer water table, the quadrangle is converted into a horizontal rectangle (figure 4.10 b and 4.11). The lengths of the boundaries L_1 and L_2 [m] are calculated with

$$L_1 = D_c + D_d \quad (4.44)$$

$$L_2 = D_a + D_b \quad (4.45)$$

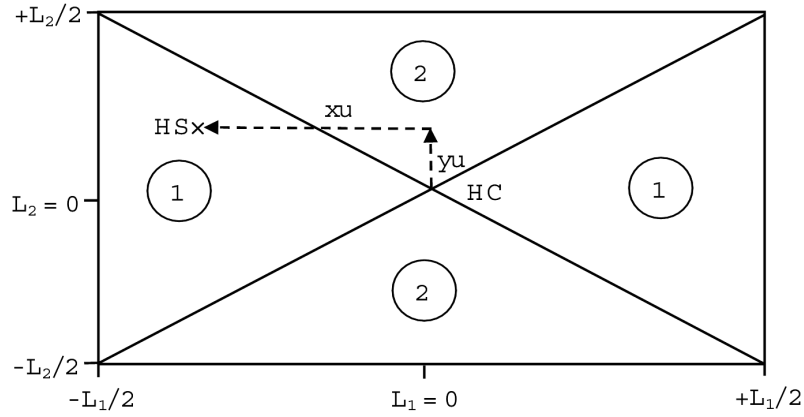


Figure 4.11: Rectangle for calculation of the groundwater mound of the mean summer water table of the quadrangle in PMDSS.

where $L_1 > L_2$.

The mean thickness of the water column without groundwater mound in the rectangle Hr [m] is calculated with

$$Hr = HC_0 - Hbal \quad (4.46)$$

where $Hbal$ [m ASL] = the bottom of the aquifer layer.

The groundwater mound of the mean summer water table at sector centre HC_m [m] is calculated with

$$HC_m = \left(\sqrt{\frac{qCWB + qGWS}{4 \cdot ksat} \cdot \sqrt{\frac{4 \cdot L_1 + L_2}{L_2}} \cdot \left(\frac{L_1 \cdot L_2}{L_1 + L_2}\right)^2 + Hr^2} \right) - Hr \quad (4.47)$$

Thus the mean summer water table at sector centre HC [m ASL] is

$$HC = HC_0 + HC_m \quad (4.48)$$

The groundwater mound of the mean summer water table at site centre HS_m [m] depends on the location of the site centre within the quadrangle (figure 4.11).

If the site centre lies within location 1 (figure 4.11) then

$$HS_m = HC_m \cdot (1 - 4/L_1^2 \cdot xu^2) \quad (4.49)$$

where xu = distance of site centre to sector centre in x direction [m] and is calculated with

$$\begin{aligned} \text{if } D_d \leq D_c \text{ then } xu &= L_1/2 - D_d \\ \text{if } D_d > D_c \text{ then } xu &= L_1/2 - D_c \end{aligned} \quad (4.50)$$

If the site centre is within location 2 (figure 4.11) then

$$HS_m = HC_m \cdot (1 - 4/L_2^2 \cdot yu^2) \quad (4.51)$$

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where y_u = distance of site centre to sector centre in y direction [m] and is calculated with

$$\begin{aligned} \text{if } D_b \leq D_a \text{ then } y_u &= L_2/2 - D_b \\ \text{if } D_b > D_a \text{ then } y_u &= L_2/2 - D_a \end{aligned} \quad (4.52)$$

Parallel flow

The theoretical water table without net recharge of sector centre HC_0 [m ASL] is calculated with

$$HC_0 = \frac{H_c + H_d}{2} \quad (4.53)$$

where H_c = the mean summer water table at boundary c [m ASL] and H_d analogical.

The theoretical water table without net recharge of the site centre HS_0 [m ASL] is calculated with

$$HS_0 = H_c + (H_d - H_c) \cdot \frac{D_c}{L} \quad (4.54)$$

where D_c = The distance of the site centre to the boundary c [m] and L = the distance between boundary c and d [m].

For the calculation of the groundwater mound of the mean summer water table, horizontal flow is assumed. The groundwater mound of the mean summer water table at sector centre HC_m [m] is calculated with

$$HC_m = \left(\sqrt{\frac{qCWB + qGWS}{4 \cdot k_{sat}} \cdot L^2 + Hr^2} \right) - Hr$$

where Hr = mean summer water table at the two boundaries [m] calculated with equation 4.46.

The mean summer water table at sector centre HC [m ASL] is calculated with equation 4.48.

The groundwater mound of the mean summer water table at site centre HS_m [m] is calculated with

$$HS_m = HC_m \cdot (1 - 4/L^2 \cdot xu^2) \quad (4.55)$$

where xu = distance of site centre to sector centre in x direction [m] and is calculated with

$$\begin{aligned} \text{if } D_d \leq D_c \text{ then } xu &= L/2 - D_d \\ \text{if } D_d > D_c \text{ then } xu &= L/2 - D_c \end{aligned} \quad (4.56)$$

Circle

The theoretical water table without net recharge of sector centre HC_0 [m ASL] is

$$HC_0 = H_a \quad (4.57)$$

where H_a = the mean summer water table at the circle boundary [m ASL].

The theoretical water table without net recharge of the site centre HS_0 [m ASL] is

$$HS_0 = H_a \quad (4.58)$$

The groundwater mound of the mean summer water table at sector centre HC_m [m] is calculated with

$$HC_m = \left(\sqrt{\frac{qCWB + qGWS}{2 \cdot k_{sat}} \cdot R^2 + Hr^2} \right) - Hr \quad (4.59)$$

where R = radius of the circle [m] and H_r = summer water table at the circle boundary [m] calculated with equation 4.46.

The mean summer water table at sector centre HC [m ASL] is calculated with equation 4.48.

The groundwater mound of the mean summer water table at site centre HS_m [m] is calculated with

$$HS_m = \left(\sqrt{\frac{qCWB + qGWS}{2 \cdot ksat} \cdot (R^2 - (R - D_a)^2) + H_r^2} \right) - H_r \quad (4.60)$$

where D_a is the distance of the site centre to the circle boundary [m].

4.3.8 Presentation of results

The major model results of PMDSS are the indicator values (land use category, harvest of plant products, mean summer water table, nitrogen discharge, Global Warming Potential, conservation value of plants) to demonstrate long-term changes of peatland functions (table 4.1 on page 13). Beside the indicators, also additional parameters (input parameters, intermediary results), such as subsidence rate, CO₂-emission, CH₄-emission, N₂O-emission, N-mineralization (table 5.6 on page 66), are presented in the result worksheets. This gives the user additional information to aid the interpretation of the results of the indicators. For instance, the values for the different greenhouse gases help to interpret the proportion of different gases resulting into GWP. The results are presented in four worksheets of PMDSS in form of:

- time series values (worksheet *Results*),
- summary of values and text output for selected years (worksheet *Res_Sum*),
- time series graphs (worksheet *Res_TimeSeries*), and
- in an amoeba diagram (worksheet *Res_Amoeba*).

Time series values are presented for the indicators and additional parameters for 100 years in area unit per year (ha⁻¹ a⁻¹). For the parameters 'subsidence' and the different greenhouse gas emission rates, cumulative values are generated (on annual basis).

Values for selected years (year 1, 2, 50, and 100) are extracted from time series values and are presented in one worksheet to give an overview of the results. For the parameters GWP (time horizons 20, 100, 500), N-discharge, and harvest of plant products, the values are converted to the site area. Thus, statements concerning site related balances are possible.

Table 4.11: Conversion number n_i for equation 4.61.

Indicator i	n_i
Harvest of plant products	0.1
Mean summer water table	51
Nitrogen discharge	0.1
Global Warming Potential	1
Conservation value of plants	0.01

Text output was integrated into PMDSS. The range of values for each parameter was subdivided into different categories (e.g. low, medium, high, very). The difference of the value of a parameter between model year 2, 50, or 100 and the initial state (model year 1) was calculated and categorized (e.g. no significant change, moderate loss, loss not acceptable, moderate improvement, important improvement). An example of this text output is described in detail for the conservation value in chapter 4.3.3.2 on page 25. Further text output is integrated from the vegetation module: economic value (chapter 4.3.3.3 on page 26) and recommendations for planning (on page 25).

Most time series values are visualized in **time series diagrams** to demonstrate the long-term changes of peatland functions (for example figure 6.3 on page 77).

In an **amoeba diagram**, the relative changes of all indicators over 50 years are combined into one graph (TEN BRINK *et al.* 1991). To represent all indicators with their different units in an amoeba diagram, the results are converted into relative values. The relative value of the initial state $R_{i,1}$ of each indicator i is set to 1. The direction of change of each indicator 50 years later, $R_{i,50}$ is calculated with:

$$R_{i,50} = (V_{i,50} + n_i) / (V_{i,1} + n_i) \quad (4.61)$$

where $V_{i,50}$ = the value of the indicator i after a simulation of 50 years, n_i = a conversion number for indicator i (table 4.11) and $V_{i,1}$ = the value of the indicator i in the initial state (model year 1). The conversion number n_i is needed in order to calculate only with positive values and to have no divisions through zero.

The maximum of $R_{i,50}$ is set to 2.6 and the maximal axis value in the amoeba diagram was set to 2. An example of an amoeba diagram is given in figure 6.4a on page 78, which is the output of the same model run as originated for the time series graph, figure 6.3. The grey line (blue colour in the PMDSS file) show the initial values $R_{i,1}$ and the black lines (red colour in the PMDSS file) show the relative changes of the indicators 50 years after the initial state $R_{i,50}$. With the amoeba approach the results are clearly arranged within one graph and different scenarios are easily comparable (for example figure 6.4 (a) through to (f) on page 78).

The results of PMDSS are to be interpreted as an orientation for a development trend of the site. Although model results are given as exact values, the user should interpret only the development direction and the order of magnitude. This is supported with result presentation as graphs, especially the amoeba diagrams and the text output. Graphs give a visual impression on how the indicators are changing. Text output helps to interpret the order of magnitude of the results. A detailed documentation of the model results is presented in chapter 5.3 on page 66.

5 Documentation of PMDSS input and result parameters

The equations and rules included in the PMDSS module worksheets were specified in the last chapter. This chapter gives an overview of the PMDSS structure and describes all input and result parameters and worksheets. It is thus a documentation for the user, needed to apply PMDSS. This is the background knowledge for the case studies in chapter 6.

5.1 Structure of PMDSS

PMDSS is a spreadsheet program in Excel (downloadable at PMDSS:<http://www.ecology.uni-kiel.de/~akniess/PMDSS>) which is subdivided into 24 worksheets (table 5.1). The first worksheet *Info* contains general model information, such as model version, names, and addresses of model developers and a short description of the worksheets (as in table 5.1). For using PMDSS, mainly the input and result worksheets are needed.

Input

Necessary input has to be entered in worksheet *Input_Par*. Input into the worksheets *Input_Hydro*, *Input_TimeSeries* and into the grey fields of worksheet *Input_Tab* are optional. Two module worksheets (*Mod_Adj* and *Mod_Veg4*) can be used for inclusion of own model equations and vegetation relevees.

Results

For a first overview, it is recommended to look at the graphs in the worksheets *Res_TimeSeries* and *Res_Amoeba*. In the worksheet *Results*, all time series values are presented. In the worksheet *Res_Sum*, results for the years 1, 2, 50, and 100 are presented in different formats. The worksheet *Res_Copy* contains copies of input and result values; this is useful for comparing different scenarios or sites.

Modules

Calculations done in the module worksheets are described in the last chapter. Usually, the user does not have to care about these worksheets.

Table 5.1: PMDSS worksheets and their contents.

Part	Worksheet	Content
General	Info	General information about the model
Input	Input_Par	Input of parameters
	Input_Hydro	Hydrology module: input and result to calculate the mean summer water table
	Input_TimeSeries	Input of parameters as time series
	Input_Tab	Look up tables used for the input and the modules, adjustment possibility of parameters
Results	Results	Result values presented as time series
	Res_Sum	Results for the years 1, 2, 50, and 100 in different formats (per ha, relative change, text, converted to the site area, recommendations)
	Res_TimeSeries	Results visualized in time series graphs
	Res_Amoeba	Results visualized in amoeba diagrams
	Res_Copy	Input and results summarized in one table for copying them into another Excel-file for comparing scenarios
	Res_Tab	Look up tables used for the presentation of the results
Modules	Mod_Adj	Adjustment possibility for subsidence rate, CO ₂ -emission, and N-mineralization
	Mod_Sub	Module: calculation of subsidence and mean summer water table
	Mod_LU	Module: calculation of land use change
	Mod_C	Module: calculation of CO ₂ - and CH ₄ - emission
	Mod_N	Module: calculation of N-discharge, N ₂ O-emission and harvest
	Mod_GWP	Module: calculation of the GWP (Global Warming Potential)
	Mod_Veg1	Vegetation module: calculation of conservation value
	Mod_Veg2	Vegetation module: development of coverage of plant groups
	Mod_Veg3	Vegetation module: calculation of potential standing crop and economic value
	Mod_Veg4	Vegetation module: possibility for entering new vegetation relevees
	Mod_Veg5	Vegetation module: potential standing crop production and N-fixation for use in N-module
	Mod_Hydro1	Hydrology module: calculation of mean summer water table
	Mod_Hydro2	Hydrology module: calculation and results of mean summer water table

PMDSS.xls									
1	Input		Initial state			Change			Comments
2	Parameter	Unit	Value	Description	Range / Default	Value	Description	Range / Default	
3	Site Name	-	Eider Valley, di						
4	Scenario	-	E (intensive grassland)						
5	Area	ha	0.175						
6	Peat thickness	m	3.5		>= 0.3				
7	Impermeable layer below peat ?	yes = 1, no = 0	1		0				
8	Clay layer thickness near surface	m	0		>=0 and <=3.2				
9	Land use number	1 to 12	11	Short time abandonment, species rich		4	Grassland, intensive mowing + pasture		
10	Surface level	m ASL	14.90		> 13.78				Instead of ASL you
11	Lowest possible water table	m ASL	13.50		< 14.62	13.50		< 14.49	e.g. lowest water le
12	Mean summer water table	cm below surface	22		> 5 and < 140	35		>= 25 and <= 140	
13	Standard deviation of water table	cm	6		10	6		10	Influence only on N
14	Air temperature	°C	8.3		>= 0 and <= 25				
15	N-Deposition	kg N/ ha/ a	28		28.22				Default value is cal
16	N-Deposition	mg N/ l	1.7		1.7				Only used for calcu
17	Precipitation	mm/ a	830						Only used for calcu
18	N-Fertilizer	kg N/ ha/ a	0		0	150		150	
19	Dying biomass after rewetting	t dry matter/ ha/ a	0		0	0		0	This value is used
20	Water type	1, 5, 10	5	mixed water		5	mixed water	5	ground water = 10,
21	Field crop / forest	grain, maize, forest, others	others		others	others		others	Only relevant for la
22	Country	G, N, NL, PL, SW, UK	G	Germany					Britain = UK , Germ
23									
24									
25	Parameters for adjustment								
26	Subsidence factor		1		1	1		1	
27	Use of subsidence factors in Input_Tab	yes = 1, no = 0	0		0				
28	Inserting new equations in Mod_Adj	yes = 1, no = 0	0		0				
29									
30	Inserting new vegetation relevee	yes = 1, no = 0	0		0				
31	Column of relevee in Mod_Veg4	Letter of column in Mod_veg4	K						
32									
33	Use of Input_TimeSeries	yes = 1, no = 0	0		0				
34	Use of Hydrology module (Input_Hydro)	yes = 1, no = 0	0		0				
35									
36									
37									

Figure 5.1: Input worksheet *Input_Par* in Excel file PMDSS.xls.

5.2 Input

5.2.1 Main input

Necessary for the use of PMDSS is the input into worksheet *Input_Par* (figure 5.1). In this worksheet, input for 'initial state' and 'change' (in second model year) is necessary for the parameters with bold letters into the value column (light green or orange background colour). Depending on the setting of the parameters for adjustment, no input into other worksheets is needed.

The input parameters are separated into two blocks:

- Initial state:
(green colour) Input parameters of the initial state (first model year)
- Change:
(red colour) Input parameters which change in the second model year in order to run scenarios with different land use and water management. To run a 'business as usual' scenario, the values have to be set to the same value as in the initial state.

Each block is separated into three columns:

- Value:
(light colour) Column for input parameters
- Description:
(dark colour) Display of long name of some input numbers or letters and other explanations
- Range/ Default:
(dark colour) Display of a default value or the range of valid input values

Further columns:

- Comments:
Description, explanation, or input assistance for some parameters

Input parameters are described in detail in table 5.2. For choosing the 'land use category' as well as for choosing the right vegetation type for the initial state, table 5.3 should be consulted, .

Table 5.2: Main input parameters.

Parameter	Unit	Description
Site Name	-	Name of the site
Scenario	-	Name of the scenario
Area	ha	Area of the simulated site
Peat thickness	m	The peat thickness of the site, including all peat horizons

5 Documentation of PMDSS input and result parameters

(continuation of table 5.2)

Parameter	Unit	Description
Impermeable layer below the peat ?	yes = 1, no = 0	Put 1, if there is an impermeable layer below peat, such as clay or gyttja.
Clay layer thickness near surface	m	Thickness of clay layer within the peat
Land use number	1 to 12	The land use number is corresponding to the land use categories which can be looked up in table 5.3. While choosing a land use category of initial state, the associated vegetation type should be considered (table 5.3). Further parameters related to the land use category are listed in table 5.5 (harvested proportion of biomass, water table limit, next land use category with lower water table, N-fertilizer). If the land use category is changing from third model year on, the associated N-fertilizer rate is taken automatically.
Surface level	m ASL	The mean elevation of the surface of the site (in relation to a reference level).
Lowest possible water table	m ASL	The maximal drainage depth is a boundary condition for the model. The mean summer water table (in m ASL) cannot get lower than this value. This maximal depth can be the lowest water level of pumping station or the mean water table of surface water. It has to be the same reference level as used for the surface level. This parameter is not used if parameter 'Use of Hydrology module (Input_Hydro)' = 1.
Mean summer water table	cm below surface	The mean summer water table below the surface of the site. This is usually the mean water table during the vegetation period. This parameter is not used if parameter 'Use of Hydrology module (Input_Hydro)' = 1.
Standard deviation of water table	cm	Water table fluctuations of the same summer period as used for the mean summer water table. This parameter influences the N ₂ O-emission.
Air temperature	C	The mean annual air temperature. This parameter influences the mineralization of the peat.
N-deposition	kg N ha ⁻¹ a ⁻¹	The N-deposition of the site includes dry and wet deposition. The default value is calculated with N-concentration * precipitation / 100 * 2.
N-concentration	mg N/l	Concentration of N in the rain water Used for calculation of the default value of N-Deposition [kg N ha ⁻¹ a ⁻¹].
Precipitation	mm/ a	Mean annual precipitation.
N-fertilizer	kg N ha ⁻¹ a ⁻¹	The mean annual N-fertilizer (organic and mineral). The default value is dependent on the land use category (table 5.5).
Dying biomass after rewetting	t dry matter ha ⁻¹ a ⁻¹	This parameter accounts for additional N-input due to dying plants after rewetting.
Water type	1, 5, 10	1 = rain water, 5 = mixed water, 10 = ground water This parameter is relevant for land use category 9 for initial vegetation type and vegetation development (see table 5.3).
Field crop/ forest	grain, maize, forest, others	The parameter is used for the vegetation module and is relevant for land use 1 (arable land) and 2 (forest).
Country	[G, N, NL, PL, SW, UK]	On the basis of the red list of the selected country, the conservation value is determined.
Parameters for adjustment		
Subsidence factor	-	Factor for own calibration of subsidence rate. Calculated subsidence rate, CO ₂ -emission, and N-mineralization are further multiplied with this factor.

(continuation of table 5.2)

Parameter	Unit	Description
Use of subsidence factors in <i>Input_Tab</i>	yes = 1, no = 0	If the user puts 1 for yes, subsidence factors of the table in <i>Input_Tab</i> are used if the land use changes automatically from 3rd model year onward.
Inserting new equations in <i>Mod_Adj</i>	yes = 1, no = 0	If the user puts 1 for yes, the equations for subsidence rate, CO ₂ -emission and N-mineralization in the worksheet <i>Mod_Adj</i> are used. The user can put own equations into this worksheet (chapter 5.2.5).
Inserting new vegetation relevee	yes = 1, no = 0	If the user wants to use data from an own vegetation plot (from worksheet <i>Mod_Veg4</i>), this parameter has to be set to 1 for yes (chapter 5.2.6).
Column of relevee in <i>Mod_Veg4</i>	Letter of column in <i>Mod_Veg4</i>	If the user wants to use data from an own vegetation plot, this parameter has to be set to the corresponding letter of the column in <i>Mod_Veg4</i> with the own data (chapter 5.2.6).
Use of <i>Input_TimeSeries</i>	yes = 1, no = 0	If the user puts 1 for yes, the input values of the worksheet <i>Input_TimeSeries</i> are used (chapter 5.2.3).
Use of Hydrology module (<i>Input_Hydro</i>)	yes = 1, no = 0	If the user puts 1 for yes, the input values of the worksheet <i>Input_Hydro</i> are used to calculate the mean summer water table (chapter 5.2.2).

5 Documentation of PMDSS input and result parameters

Table 5.3: Land use categories and associated vegetation types used as standard input in PMDSS (associated parameters see table 5.5 on page 64). For the vegetation type, input for mean summer water table and water type are only relevant at land use category 9 and 12 respectively.

Input parameters			Associated specifications	
Land use category	Mean summer water table	Water type	Vegetation type	Detailed description of typical land use associated to vegetation type
[1-12]	[cm below surface]	[1, 5, 10] ^a	[-]	[-]
1	Arable land		Field	
2	Forest		Alder forest	
3	Grassland, intensive mowing		Forage grassland	> 2 cuts/a, > 2 cattle/ha, min. + org. fertilizer, pasture maintenance
4	Grassland, intensive mowing + pasture			
5	Grassland, intensive pasture		Wet meadow	2 cuts/a, < 2 cattle/ha, often without min. + org. fertilizer
6	Grassland, moderate mowing			
7	Grassland, moderate mowing + pasture			
8	Grassland, moderate pasture			
9	Nature conservation management	1, 5	Small sedges base poor	1 cut/a, < 1 cattle/ha, no fertilizer
		10	Small sedges base rich	
10	Short time abandonment, species poor		Urtica community	intensive land use before abandonment
11	Short time abandonment, species rich		Abandoned grassland	mowing/ grazing not every year, no fertilizer
12	None	≥ 5	Alder forest	
		< 5	Reed	

^a1 = rain water, 5 = mixed water, 10 = calcareous ground water

5.2.2 Input for the hydrology module

If the user wants to use the hydrology module, input into worksheet *Input_Hydro* is necessary and the parameter 'Use of Hydrology module (Input_Hydro)' in worksheet *Input_Par* has to be set to 1. The setup is similar to worksheet *Input_Par*. The cells with light green or orange background colour are the input cells.

The input parameters are separated into two blocks:

- Initial state:
(green colour) Input parameters of the initial state (first model year)
- Change:
(red colour) Input parameters which change in the second model year in order to run scenarios with different land use and water management. To run a 'business as usual' scenario, the values have to be equal to the initial state.

Each block is separated into two columns:

- Value:
(light colour) Column for input parameters
- Description/ Range/ Default:
(dark colour) Display of long name of some input numbers or letters, display of default value, the range of valid input values, or if the parameter is used

In the grey row, the calculated mean summer water table can be adjusted to a value given by the user:

- The mean summer water table can be adjusted to the value given by the user in the light grey cell.
- By pressing one of the two grey buttons 'Change of ksat value of peat layer' or 'Change of climatic water balance', the mean summer water table will be adjusted automatically to the mean summer water table given by the user. This results in an automatic change of the input value of ksat of the peat layer or mean climatic water balance of summer respectively.

The results of the mean summer water table for the first 2 years are given in the yellow box. They can be checked, as to their accordance to other input values, such as land use category.

Input parameters are described in detail in table 5.4.

Table 5.4: Input parameters for the hydrology module.

Parameter	Unit	Description
Geometry of hydrological sector	[q, p, c]	First, the user has to choose the basic geometry of the hydrological sector: q = quadrangle, p = parallel flow, c = circle (figure 4.9 on page 47). The investigated site lies within the hydrological sector or might be the same. The hydrological sector is an area with defined hydrological boundary conditions (surrounding water tables). The quadrangle might be for instance a situation, where the the sector is surrounded by two ditches (boundaries a and b), a river (boundary d) and a fourth border (boundary c) with groundwater inflow to the sector (higher elevation than site). The parallel flow might be the same situation without ditches. The circle might be an ombotrophic peatland with the same water table surrounding it.
Geometry of sector		
Mean summer water table at boundary a	m ASL	Mean summer water table at boundary a of the sector (quadrangle) or the water table of the boundary (circle)
Mean summer water table at boundary b	m ASL	Mean summer water table at boundary b of the sector (quadrangle)
Mean summer water table at boundary c	m ASL	Mean summer water table at boundary c of the sector (quadrangle, parallel flow)
Mean summer water table at boundary d	m ASL	Mean summer water table at boundary d of the sector (quadrangle, parallel flow)
Length a	m	Length of boundary a of the sector (quadrangle) or diameter (circle)
Length b	m	Length of boundary b of the sector (quadrangle)
Length c	m	Length of boundary c of the sector (quadrangle, parallel flow)

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(continuation of table 5.4)

Parameter	Unit	Description
Length d	m	Length of boundary d of the sector (quadrangle, parallel flow)
Distance of site centre to a	m	Distance from site centre to boundary a (quadrangle) or to the boundary (circle)
Distance of site centre to b	m	Distance from site centre to boundary b (quadrangle)
Distance of site centre to c	m	Distance from site centre to boundary c (quadrangle, parallel flow)
Distance of site centre to d	m	Distance from site centre to boundary d (quadrangle, parallel flow)
Soil profile of hydrological sector		
Number of layers	2 or 3	Number of layers in the soil profile
Layer 1 (Peat layer)	w, s, l	Permeability of the first layer (well, semi-, or low permeable). This parameter is used to derive the default value for the saturated hydraulic conductivity of layer 1 (ksat 1).
Thickness layer 1	m	Thickness of soil layer 1
ksat 1	m d ⁻¹	Saturated hydraulic conductivity of layer 1
Layer 2	w, s, l, i	Permeability of the second layer (well, semi-, or low impermeable). This parameter is used to derive the default value for the saturated hydraulic conductivity of layer 2 (ksat 2).
Thickness layer 2	m	Thickness of soil layer 2
ksat 2	m d ⁻¹	Saturated hydraulic conductivity of layer 2
Layer 3	w, s, l, i	Permeability of the third layer (well, semi-, or low impermeable). This parameter is used to derive the default value for the saturated hydraulic conductivity of layer 3 (ksat 3).
Thickness layer 3	m	Thickness of soil layer 3
ksat 3	m d ⁻¹	Saturated hydraulic conductivity of layer 3
Further parameters		
Mean climatic water balance of summer	mm	= precipitation - evapotranspiration of the summer period (vegetation period)
Groundwater seepage in summer	mm	Upward/ downward groundwater seepage of the summer period (vegetation period). Positive values account for upward and negative values for downward seepage.
Adjustment of mean summer water table		
Adjust mean summer water table to	cm below surface	Value of the mean summer water table of the initial state to which the user wants to adjust to the calculated mean summer water table (by changing either mean climatic water balance of summer or ksat 1).

5.2.3 Parameter changes after the second model year

For some input parameters in PMDSS, it is possible to change them every year during the whole simulation period in worksheet *Input_TimeSeries* (the parameter 'Use of Input_TimeSeries') in worksheet *Input_Par*

has to be put to 1):

- Lowest possible water table [m ASL]:
This parameter might be changed within the simulation period to account for water management changes.
- Mean summer water table [cm below surface]:
To account for regular redrainage, the mean summer water table may be set e.g. to the same value every 10th year.
- Air temperature [$^{\circ}\text{C}$]:
To account for global warming, the air temperature can steadily be increased over 100 years.
- N-fertilizer [$\text{kg N ha}^{-1} \text{ a}^{-1}$]:
If the model is automatically changing land use category, the standard value for N-fertilizer is used. If the user wants to use a different value instead, this value can be set in this worksheet at the relevant year with land use change.
- Dying biomass after rewetting [$\text{t dry matter ha}^{-1} \text{ a}^{-1}$]:
If the mean summer water table is increasing abruptly, this parameter might be set to account for nitrogen input due to dying biomass.
- Mean summer water table at boundary a, b, c, and d [cm below surface]:
If the hydrology module is used, the summer water tables of the boundaries (ditches, river, groundwater) are to be changed instead of the summer water table of the site. To account for regular redrainage, the mean summer water tables at the boundaries may be set e.g. to the same value every 10th year.

5.2.4 Parameter adjustments

The values in worksheet *Input_Tab* are used in the modules as a look up table for different parameters. Parameters in the grey cells may be changed by the user in order to adjust PMDSS (standard values of the first four parameters in table 5.5).

- Harvested proportion of standing crop production [0 - 1]:
Fraction of the plant biomass which is harvested. This parameter is used in the nitrogen module for calculating the harvest of plants (chapter 4.3.5.2.2 on page 38).
- Water table limit [cm below surface]:
If the mean summer water table is getting lower than the water table limit, the model is automatically switching to the 'next land use category with lower water table'.
- Next land use category with lower water table [-]:
The water table limit of the next land use category has to be lower than that of the actual land use category. This parameter cannot be set to land use category 10 or 11.

Table 5.5: Land use categories and associated parameters (associated vegetation types see table 5.3 on page 60).

Land use category	Harvested proportion of biomass	Water table limit	Next land use category with lower water table	N-fertilizer
[1-12]	[0 - 1]	[cm below surface]	[-]	[kg N ha ⁻¹ a ⁻¹]
1 Arable land	0.95	50	3	200
2 Forest	0.50	5	12	0
3 Grassland, intensive mowing	0.80	25	6	150
4 Grassland, intensive mowing + pasture	0.70	25	7	150
5 Grassland, intensive pasture	0.15	25	8	125
6 Grassland, moderate mowing	0.80	15	9	75
7 Grassland, moderate mowing + pasture	0.70	15	9	60
8 Grassland, moderate pasture	0.15	15	9	60
9 Nature conservation management	0.70	5	12	0
10 Short time abandonment, species poor	0.00	5	12	0
11 Short time abandonment, species rich	0.00	5	12	0
12 None	0.00	-50	12	0

- N-fertilizer [kg N/ ha/ a]:

This value appears as default the value for the input parameter N-fertilizer. If the land use is automatically switching to the next land use category, the model calculates with this default fertilizer value. If another value is wanted in this case, there is the possibility to put values in the worksheet *Input_TimeSeries* for the parameter N-fertilizer.

- Subsidence calibration factor [-]:

Factor for own calibration of subsidence rate. The standard value is 1. Calculated subsidence rate, CO₂-emission and N-mineralization are further multiplied with this factor. For model year 1 and 2, this factor can be changed in worksheet *Input_Par*. If land use is changing, the values from worksheet *Input_Tab* are used by the model if parameter 'Use of subsidence factors in Input_Tab' in worksheet *Input_Par* is set to 1.

- Distribution of DIFF:

Parameters such as factor fn of table 4.8 (on page 40) can be changed in this table. This factor has an effect on the amount of calculated N-discharge and N₂O-emission.

5.2.5 Adjustment with user defined equations

In worksheet *Mod_Adj*, own equations for subsidence rate of surface [cm a⁻¹], CO₂-emission [kg C ha⁻¹ a⁻¹] and N-mineralization [kg N ha⁻¹ a⁻¹] can be included. They are then used instead of the model internal equations if the parameter 'Inserting new equations in Mod_Adj' in worksheet *Input_Par* is set to 1.

5.2.6 Input of user defined vegetation data

For inserting a vegetation plot, the parameter 'Inserting new vegetation relevee' has to be set to 1 in worksheet *Input_Par*. The data from the vegetation plot has to be stored into a new column on worksheet

Mod_Veg4. The parameter 'Column of relevee in Mod_Veg4' in worksheet *Input_Par* has to be set to the letter of the column.

To insert a new vegetation relevee from a peatland site, the species list from the site has to be joined with the species list in Annex C (downloadable as Excel file from the PMDSS homepage at http://www.ecology.uni-kiel.de/~akniess/PMDSS/Veg_Docu_Annex.xls). Then, species have to be grouped to plant groups with same values for the abandonment category, intensification category, water source, and water table. The percentage of cover of each plant group is to be calculated. Before inserting the vegetation plot in the model, the coverage has to be converted, so that the sum of cover of all plant groups is equal to 1.

5.3 Results

5.3.1 Result parameters

Result parameters are indicator values and additional parameters (table 5.6). For the parameters subsidence, CO₂-emission, CH₄-emission, and N₂O-emission, also cumulative values are generated. With the additional parameters, help for the interpretation of indicator values is provided. The dependency between input parameters and result parameters is presented in a matrix (table 5.7).

Table 5.6: Result parameters.

Parameter	Unit	Description
Indicators		
Mean summer water table	cm below surface	The mean summer water table of the site is mainly changing due to subsidence (page 20) and change in water management (input in worksheets <i>Input_Par</i> , <i>Input_TimeSeries</i> or <i>Input_Hydro</i>).
Nitrogen discharge	kg N ha ⁻¹ a ⁻¹	Nitrogen discharge includes the discharge of NO ₃ , NH ₄ , and DON (chapter 4.3.5.2.3 on page 40).
GWP (20 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential of greenhouse gas emission (CO ₂ , CH ₄ , and N ₂ O) over the time horizon of 20 years (chapter 4.3.6.2 on page 42).
GWP (100 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential of greenhouse gas emission (CO ₂ , CH ₄ , and N ₂ O) over the time horizon of 100 years (chapter 4.3.6.2 on page 42).
GWP (500 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential of greenhouse gas emission (CO ₂ , CH ₄ , and N ₂ O) over the time horizon of 500 years (chapter 4.3.6.2 on page 42).
Harvest	t dry matter ha ⁻¹ a ⁻¹	Harvest of plant products is calculated in the nitrogen module (chapter 4.3.5.2.2 on page 38). Depending on the land use category, a proportion of the standing crop production is taken as harvest. In terms of milk and meat production, this indicator accounts for the uptake of plants by animals.
Land use category	1-12	For description of land use categories see table 5.3. Land use category is an input parameter as well as a result and can change automatically due to water table rise (chapter 4.3.2.2 on page 22).
Conservation value	-	An index for the coverage of threatened plant species in the simulated area. The conservation value is based on the red lists of each project country. It is calculated by the multiplication of the weighted red list status of the plants within each plant group and the cover of the group (chapter 4.3.3.2 on page 25).
Additional parameters		
Subsidence rate of surface	cm a ⁻¹	Mainly dependent on mean summer water table and air temperature (chapter 4.3.1.2 on page 18).
Surface level	m ASL	Changing with subsidence rate (chapter 4.3.1.2 on page 18).
Peat thickness	m	Changing with subsidence rate. If peat thickness is getting lower than 30 cm, PMDSS is stopping to calculate as in this case there is no peatland left (chapter 4.3.1.2 on page 18).
CO ₂ -emission	kg C ha ⁻¹ a ⁻¹	Mainly dependent on mean summer water table and air temperature (chapter 4.3.4.2 on page 29).
CH ₄ -emission	kg C ha ⁻¹ a ⁻¹	Mainly dependent on mean summer water table and air temperature (chapter 4.3.4.2 on page 29).

(continuation of table 5.6)

Parameter	Unit	Description
N ₂ O-emission	kg N ha ⁻¹ a ⁻¹	N ₂ O-emission depends mainly on available nitrogen (fertilizer, mineralization, deposition, fixation), mean summer water table, water table fluctuations (standard deviation), peat thickness, and permeability of the layer below the peat (chapter 4.3.5.2.3 on page 40).
GWP (20 yrs), GWP (100 yrs) and GWP (500 yrs) for the gases N ₂ O and CH ₄ seperately	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential of CH ₄ -emission and N ₂ O-emission seperately, in each case over a time horizon of 20, 100 and 500 years. The GWPs for CO ₂ -emission are equal to CO ₂ -emission (compare chapter 4.3.6.2 on page 42).
N-mineralization	kg N ha ⁻¹ a ⁻¹	Mainly dependent on mean summer water table and air temperature (chapter 4.3.5.2.1 on page 37).
Standing crop production	t dry matter ha ⁻¹ a ⁻¹	This parameter is basically calculated in the vegetation module, whereas it is limited by available nitrogen and is extended to 100 years (chapter 4.3.5.2.2 on page 38). Harvest is calculated from this parameter.
Cost of harvest	low - high	Intermediary result for economic value (chapter 4.3.3.3 on page 26)
Quantity of harvest	low - high	Intermediary result for economic value (chapter 4.3.3.3 on page 26)
Quality of harvest	low - high	Intermediary result for economic value (chapter 4.3.3.3 on page 26)
Economic value	low - high	Evaluation of the combination of cost of harvest, quality, and quantity of harvest (chapter 4.3.3.3 on page 26)

5.3.2 Result worksheets

The result parameters described in the last chapter are presented in the worksheets *Results*, *Res_Sum*, *Res_TimeSeries*, and *Res_Amoeba*. In the worksheet *Res_Copy*, input parameters and result parameters are arranged in one column. The worksheet *Res_Tab* contains look up tables for text output in worksheet *Res_Sum*. The model output is described in detail in chapter 4.3.8 on page 52. The result worksheets have the following contents:

1. *Results*

This worksheet contains all result values as a time series for 100 years.

2. *Res_Sum*

In this worksheet, the results values and text output for selected years (year 1, 2, 50, and 100) are presented to give an overview of the results. The worksheet contains six blocks:

- Results (per ha):
The values of the indicators are given for year 1, 2, 50, and 100.
- Conversion:
This block is an intermediary result for the calculation of the relative values.
- Results (relative change):
The absolute values of the indicators are transferred to relative values. They are used for the amoeba graph in worksheet *Res_Amoeba*.

5 Documentation of PMDSS input and result parameters

- Results (text):
Results in text format are given in this block.
- Results converted to the site area:
The absolute values of the indicators and additional parameters are summed up for the whole area.
- Recommendations for planning:
Recommendations for planning in text format are given in this block.

3. *Res_TimeSeries*

Time series graphs of indicators and additional parameters.

4. *Res_Amoeba*

Amoeba graph of the indicators, based on values in worksheet *Res_Sum* block 'Results (relative change)'.

5. *Res_Copy*

This worksheet contains selected input and result values (in one column). For comparing scenarios, one may copy the input and result values (paste only values not the equations) from the worksheet *Res_Copy* into another Excel file and add each scenario to the new file into different columns.

6. *Res_Tab*

The tables in this worksheet are used by the model to set up text output in worksheet *Res_Sum* (column 'Results (text)'). Usually, the user does not have to care about this worksheet.

Table 5.7: Dependency matrix of input and result parameters in PMDSS. The parameters on the left site are depending on the parameters from the right site.

			Input parameters														Further parameters															
Results	Units	Calculated in worksheet	Peat thickness	Impermeable layer below peat	Clay layer thickness near surface	Land use category	Surface level	Lowest possible water table	Mean summer water table	Standard deviation of summer water table	Air temperature	N-deposition	N-fertilizer	Dying biomass after rewetting	Water type	Field crop / forest	Country	Precipitation	Subsidence factor	Subsidence rate of surface	CO ₂ -emission/-sequestration	CH ₄ -emission	N ₂ O-emission	N-mineralization	Potential standing crop	Cost of harvest	Quality of harvest	Quantity of harvest				
Indicators	Mean summer water table*	cm below surface	Mod_Subs	(x)	(x)		(x)	(x)	x												x											
	N-discharge	kg N ha ⁻¹ a ⁻¹	Mod_N	x	x		x		x			x	x	x										x	x							
	GWP (20 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Mod_GWP																			x	x	x								
	GWP (100 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Mod_GWP																			x	x	x								
	GWP (500 yrs)	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Mod_GWP																			x	x	x								
	Harvest: plant products	kg DM ha ⁻¹ a ⁻¹	Mod_N				x						x	x											x	x						
	Land use category	12 categories	Mod_LU				x		x																							
Conservation value	-	Mod_Veg1				x		x							x	x	x															
Further parameters	Subsidence rate of surface	cm/a	Mod_Subs	(x)	x	x		x			x										x											
	CO ₂ -emission/-sequestration	kg CO ₂ -C ha ⁻¹ a ⁻¹	Mod_C	(x)	x	x		x			x										x											
	CH ₄ -emission	kg CH ₄ -C ha ⁻¹ a ⁻¹	Mod_C	(x)				x													x											
	N ₂ O-emission	kg N ₂ O-N ha ⁻¹ a ⁻¹	Mod_N	x	x		x		x	x		x	x												x							
	N-mineralization	kg N ha ⁻¹ a ⁻¹	Mod_N	(x)		x	x		x			x										x										
	Potential standing crop	kg DM ha ⁻¹ a ⁻¹	Mod_Veg3				x		x							x	x	x														
	Cost of harvest	-	Mod_Veg3				x		x																							
	Quality of harvest	-	Mod_Veg3				x																				x					
	Quantity of harvest	-	Mod_Veg3																								x					
Economic value	-	Mod_Veg3																									x	x	x			

x = dependency, (x) = dependency is functioning as a limit

*If the mean summer water table is calculated with the hydrology module, the parameter is additionally depending on the mean summer water tables of the hydrological sector boundaries, geometry and size of the hydrological sector, position of the site within the sector, climatic water balance of summer, and mean saturated hydraulic conductivity of the soil profile.

6 Case studies

6.1 A peatland site in the Eider Valley, Germany

6.1.1 Purpose and motivation

Within the EUROPEAT project, a study site in the Eider Valley peatland was selected for further investigations and measurements. The Eider Valley peatland is typical for peatlands in the Weichselian landscape of northwest Germany (TREPPEL & KLUGE 2002). In order to examine the objective of work package 7 in the EUROPEAT project "determination of the effects of land use and water management and global climate change on the deterioration and restoration of selected peat soils on the field, regional and European scale" (chapter 3.1), PMDSS was applied to the selected study site. The study site was divided into two sites: discharge site and flooded site.

The following questions are to be answered with this application:

- How will the two sites develop during the next 100 years?
- How does water management and land use affect the development of the peatland functions on the sites?
- How does increased air temperature due to climate change affect the development of ecosystem functions?

To answer these questions, two scenario bundles were developed. The land use and water management scenarios focus on the actual situation at the selected peatland site and possible plausible changes in land use and water management. The climate change scenarios examine the effect of water management and temperature change at land use type intensive grassland (the typical land use type at peatland sites in northwest Germany). PMDSS version 1.14 was used for this case study.

6.1.2 Site description

The Eider Valley peatland is a minerotrophic peatland located 10 km south of Kiel (SCHRAUTZER *et al.* 2002, TREPPEL & KLUGE 2002). The valley is a hot spot for species diversity on a local scale and has a high potential for nutrient retention through a lateral buffer management. Ecohydrological measurements were carried out within a peatland site bordered by the river Eider, the upland mineral soils, and two ditches on both sites (figure 6.1). The margins near the mineral soil part are mainly influenced by groundwater discharge (site D), the areas near the river by flooding (site F).

The site has a mesotrophic to eutrophic deep peat profile with a medium degree of decomposition (Van Post scale 4) above a thick gyttja layer (figure 6.2). The mean annual water table is about 20 cm below surface. The site was used as a meadow and pasture during the past centuries. However, the selected site is abandoned since the mid 1990s. For the future, it is planned to graze the site again.

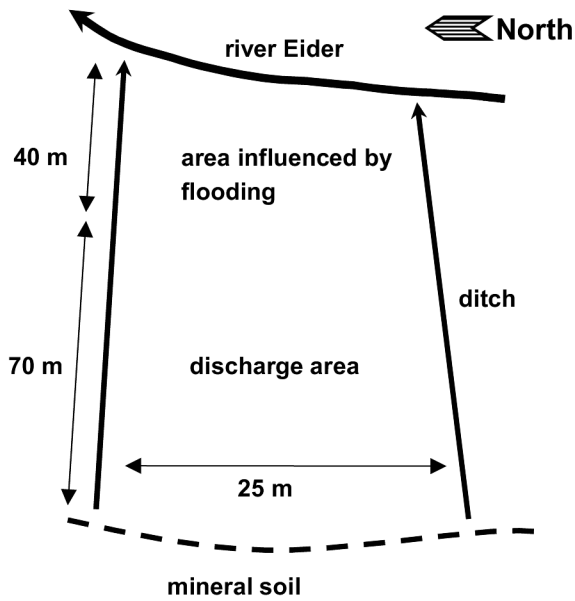


Figure 6.1: Scheme of the investigated peatland site in the Eider Valley, a minerotrophic peatland in northwest Germany.

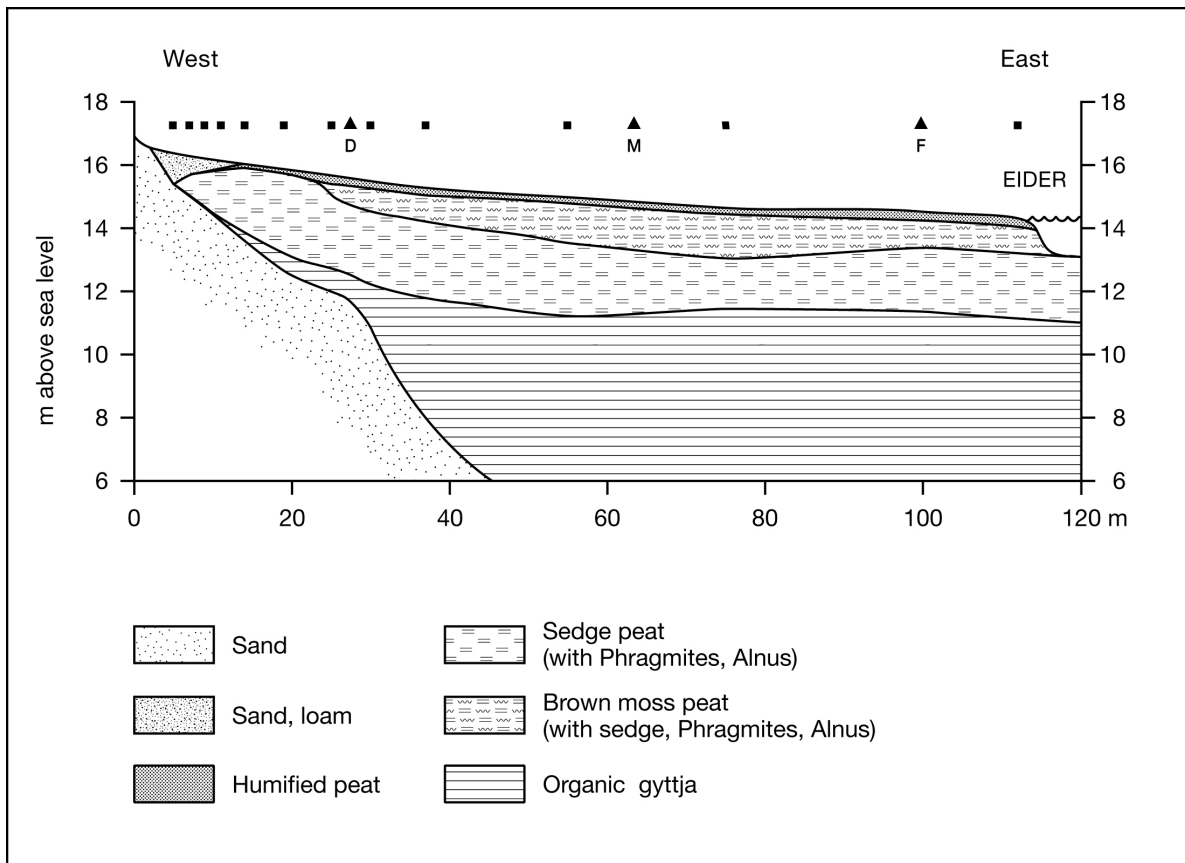


Figure 6.2: Geological cross section in the Eider Valley at the study site. The rectangles indicate the positions of the soil profile measurements (2003-2005). The triangles indicate the water table measurement points (D = Discharge site, M = Middle site, F = Flooded site).

Table 6.1: Input parameters for the initial state of the land use and water management scenarios in the Eider Valley.

Parameter	Unit	Site F (flooded)	Site D (discharge)
Site Name	-	Eider valley, flooded area	Eider valley, discharge area
Scenario	-	business as usual	business as usual
Area	ha	0.1	0.175
Peat thickness	m	3.5	3.5
Impermeable layer below the peat ?	yes = 1, no = 0	1	1
Clay layer thickness near surface	m	0	0
Land use number	1 to 12	11 ^a	11 ^a
Surface level	m ASL	14.5	14.9
Lowest possible water table	m ASL	13.5	13.5
Mean summer water table	cm below surface	30	22
Standard deviation of water table	cm	18	6
Air temperature	°C	8.3	8.3
N-Deposition	kg N/ ha/ a	28	28
N-Deposition	mg N/ l	1.7	1.7
Precipitation	mm/ a	777	777
N-Fertilizer	kg N/ ha/ a	0	0
Dying biomass after rewetting	t dry matter/ ha/ a	0	0
Water type	1, 5, 10	5	5
Field crop/ forest	grain, maize, forest, others	others	others
Country	G, N, NL, PL, SW, UK	G	G

^aLand use number 11 = land use category 'Short time abandonment, species rich'

6.1.3 PMDSS input

Land use and water management scenarios

Input data for PMDSS for the initial state of the land use and water management scenario runs (table 6.1) are based on field measurements, estimations, and literature values (table 6.2). The parameter 'land use number' was set to 11 which is according to the land use category 'Short time abandonment, species rich' and the vegetation type 'abandoned grassland' (compare table 5.3 on page 60).

For the business as usual scenario (A), values were the same in the second model year. Based on typical situations in Schleswig-Holstein, land use and water management scenarios were selected (B-E, table 6.3). In scenario B, both sites are completely rewetted, leading to a mean summer water table at (site D) or above (site F) the surface. In scenario C, the sites are used again as moderate pasture. Every 15 years, the sites are redrained, because they are getting wetter over time due to subsidence. In scenario D, the sites are used with the aim of nature conservation; thus, they are mown less than one time per year. In scenario E, the sites are drained more deeply in order to be able to use them as intensive grassland, including fertilization. No effort for further redrainage is accounted for.

Table 6.2: Data source of the input parameters for the initial state of the land use and water management scenarios of the peatland sites D and F in the Eider Valley.

Parameter	Data source
Area	Estimation from a topographical map (DGK5)
Peat thickness	Soil profile (2003 - 2005)
Impermeable layer below peat?	Soil profile (2003 - 2005)
Surface level	Levelling (2003 - 2005)
Lowest possible water table	Minimal river water table, derived from nearby gauge and own manual measurements (1992-2006)
Mean summer water table	Continuous measurements (6/2003-8/2006)
Standard deviation of water table	Continuous measurements (6/2003-8/2006)
Air temperature	Meteorological station Kiel (1961 - 1990)
N-Deposition	Literature (TREPPEL & KLUGE 2004)
Precipitation	Meteorological station Kiel (1961 - 1990)

Table 6.3: Land use and water management scenarios which were run with PMDSS for the discharge (D) and flooded (F) site in the Eider Valley. Parameters changed in comparison to initial state for site D and F.

Scenarios	Parameter changes	
	Site D (discharge)	Site F (flooded)
A Business as usual	Land use category = none (12)	Land use category = none (12)
B Rise of water level in ditches and river	Land use category = none (12); mean summer water table = 0 cm below surface; lowest possible water table raised by 50 cm	Land use category = none (12); mean summer water table = -40 cm below surface; lowest possible raised by 50 cm; dying biomass after rewetting = 10 t dm ha ⁻¹ a ⁻¹
C Moderate pasture and regular redraining	Land use category = grassland, moderate pasture (8); summer water table reset to 22 cm below surface every 15th year	Land use category = grassland, moderate pasture (8); summer water table reset to 30 cm below surface every 15th year
D Nature conservation management	Land use category = nature conservation management (9)	Land use category = nature conservation management (9)
E Intensive grassland	Land use category = grassland, intensive mowing + pasture (4); summer water table = 30 cm below surface; N-fertilizer = 150 kg N ha ⁻¹ a ⁻¹	Land use category = grassland, intensive mowing + pasture (4); summer water table = 35 cm below surface; N-fertilizer = 150 kg ha ⁻¹ a ⁻¹

Climate change scenarios

The selection of the climate change scenarios is chosen in accordance with an agreement within the EURO-PEAT project. To account for climate change, a temperature increase is used for simulations. The chosen temperature scenario is based on the A2 scenario of ECHAM data (RÄISÄNEN *et al.* 2004) for a grid position near the upper Eider Valley in northern Germany (table 6.4). In the A2 scenario, the temperature is 4.5 K higher than in the control. The precipitation is increasing by 120 mm.

Intensive grassland at the discharge site is assumed as land use for initial state. In the state Schleswig-Holstein in northwest Germany, the majority of peatlands are used as intensive grassland. Input parameters are based on table 6.1. The four parameters mean summer water table, temperature, N-fertilizer, and land use category have been changed for the climate changes scenarios (table 6.5). PMDSS was run with three different water tables with and without temperature increase.

Table 6.4: Measured and simulated long-term climate parameters for the Eider Valley peatland.

Data source		Period	Mean annual temperature [°C]	Mean annual precipitation [mm]
Meteorological station Kiel		1961 - 1990	8.3	777
Echam model	Control	1961 - 1990	8.6	990
	A2	2071 - 2100	13.1	1110
	B2	2071 - 2100	12.0	1130

Table 6.5: Climate change scenarios which were run with PMDSS for the discharge site in the Eider Valley. Parameter changes in comparison to input parameters of site D (table 6.1).

Column	Scenario	Mean Summer water table [cm below surface]	Temperature [°C]	N-Fertilizer [kg N ha ⁻¹ a ⁻¹]	Land use category
Initial state	F - L	50	8.3	150	
Change	F	50			Intensive grassland, mowing + pasture (= category 4)
	G	40	8.3	150	
	H	30			
	I	50	Linear increase		
	K	40	from 8.3 (year 2)	150	
	L	30	to 13.0 (year 100)		

6.1.4 PMDSS results

Land use and water management scenarios

First, the results of the discharge site are presented.

In the business as usual scenario (A), the mean summer water table is continuously rising due to subsidence (figure 6.3). Consequently, peat mineralization is decreasing, resulting in decreasing Global Warming Potentials during the first years and decreasing nitrogen discharge. After about 35 years, GWP_{500} is further decreasing, while GWP_{20} and GWP_{100} are increasing. This is due to starting methane emission at higher water tables. The conservation value of plants is not changing significantly. These results are also presented in an amoeba diagram (figure 6.4 a). It shows the relative change of indicators for peatland functions 50 years after the initial state (black line).

The scenario results (B-E) show that the ecosystem functions of the peatland site react visibly to the different land use and management options (figure 6.4 b-e) in comparison to scenario A (figure 6.4 a).

The active rise of the water table in scenario B (figure 6.4 b) leads to lower N-discharge and GWP_{500} due to lower peat mineralization and beginning peat growth after 10 years.

In scenario C, land use is changing from none to moderate grassland (figure 6.4 c). Thus harvest is increasing as was expected. As the site is regularly re drained in this scenario, the mean summer water table as well as the subsidence rate remain at the same level 50 years later. Therefore, the GWP_{500} does not change. With moderate grassland use, the conservation value is increasing. N-discharge increases due to less N-uptake by plants.

With land use change to nature conservation management in scenario D, the harvest is consequently increasing (figure 6.4 d). As the site is not re drained regularly in scenario D, the mean summer water table is decreasing. This results in a decrease of N-discharge and GWP_{500} . The land use change leads to an increase in conservation value.

In scenario E, land use is changed to 'intensive grassland' and the mean summer water table increased in the second model year (figure 6.4 e). About 50 years later, the mean summer water table dropped down to a slightly lower level than at the initial state due to subsidence. This in turn leads to land use change from intensive to moderate grassland. As the site gets wetter, the water table is falling below the limit for intensive grassland. Due to the land use change to moderate grassland, the conservation value increases. Harvest is increasing as to be expected. The slightly lower water table leads to a small decrease of GWP_{500} . N-discharge is increasing due to application of fertilizer.

The results of the flooded site (F) differ quantitatively from those of the discharge site (D) (table 6.6). The directions of change of the scenarios are similar. As the mean summer water table is deeper at site F than at site D, the higher subsidence rate leads to a higher cumulative GWP_{500} and N-discharge after 50 years at scenarios A, C, D, and E. At scenario B, cumulative GWP_{500} is slightly lower at site F than site D. In this case, PMDSS models higher CO_2 -sequestration rates at site F. Land use categories are equal. Water tables are lower. An exception is scenario B, where they are higher. Cumulative N-discharge is higher in all scenarios due to higher mineralization rates. Conservation values are equal in scenarios A to D and similar in scenario E as land use categories are the same. Cumulative harvest is slightly higher at site F in scenarios C to E due to higher N availability for the plants.

Table 6.6: Results of scenario runs.

Year	Scenario	Land use category ^a	Mean summer water table [cm below surface]	Cumulative N-discharge [kg N ha ⁻¹]	Cumulative GWP ₅₀₀ [kg CO ₂ -C-equ. ha ⁻¹]	Conservation value	Cumulative harvest [t dry matter ha ⁻¹]
Discharge site							
1	A-E	11	22	8	2 326	0.05	0
50	A	12	12	246	87 846	0.04	0
	B	12	0	87	23 123	0.01	0
	C	8	21	394	107 694	0.24	40
	D	9	12	255	87 883	0.27	175
	E	7	16	1236	120 448	0.41	276
1	F-L	4	50	71	4 892	0.04	7
50	F	4	28	2811	197 150	0.04	347
	G	7	22	2046	161 196	0.12	334
	H	7	16	1023	122 364	0.19	291
	I	4	26	3280	221 075	0.04	347
	K	7	20	2193	179 647	0.13	338
	L	9	15	1076	135 817	0.20	305
Flooded site							
1	A-E	11	30	12	3 151	0.05	0
50	A	12	16	397	120 713	0.04	0
	B	12	-37	95	18 478	0.01	0
	C	8	29	794	148 030	0.24	42
	D	9	16	561	121 699	0.27	187
	E	7	19	1640	146 697	0.37	312

^aLand use categories are listed in table 5.3 on page 60.

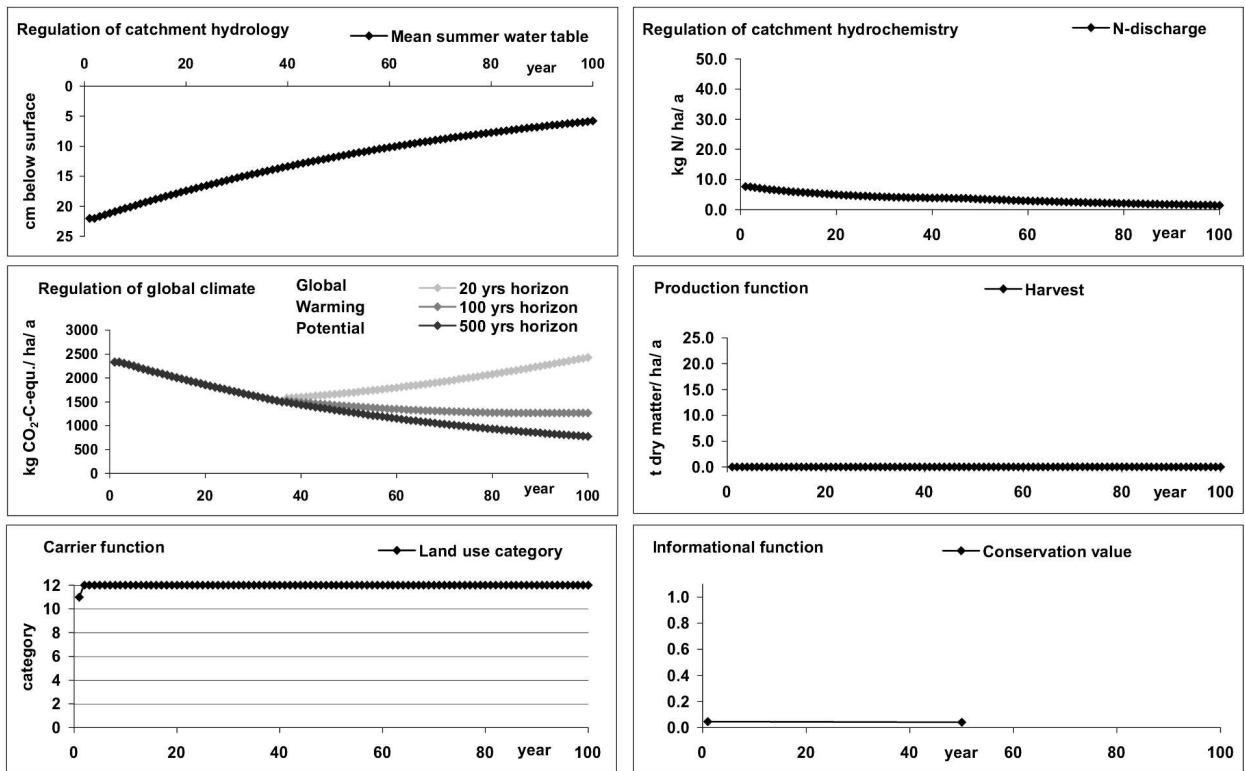


Figure 6.3: PMDSS output as time series graphs of scenario A for the discharge site (business as usual).

6 Case studies

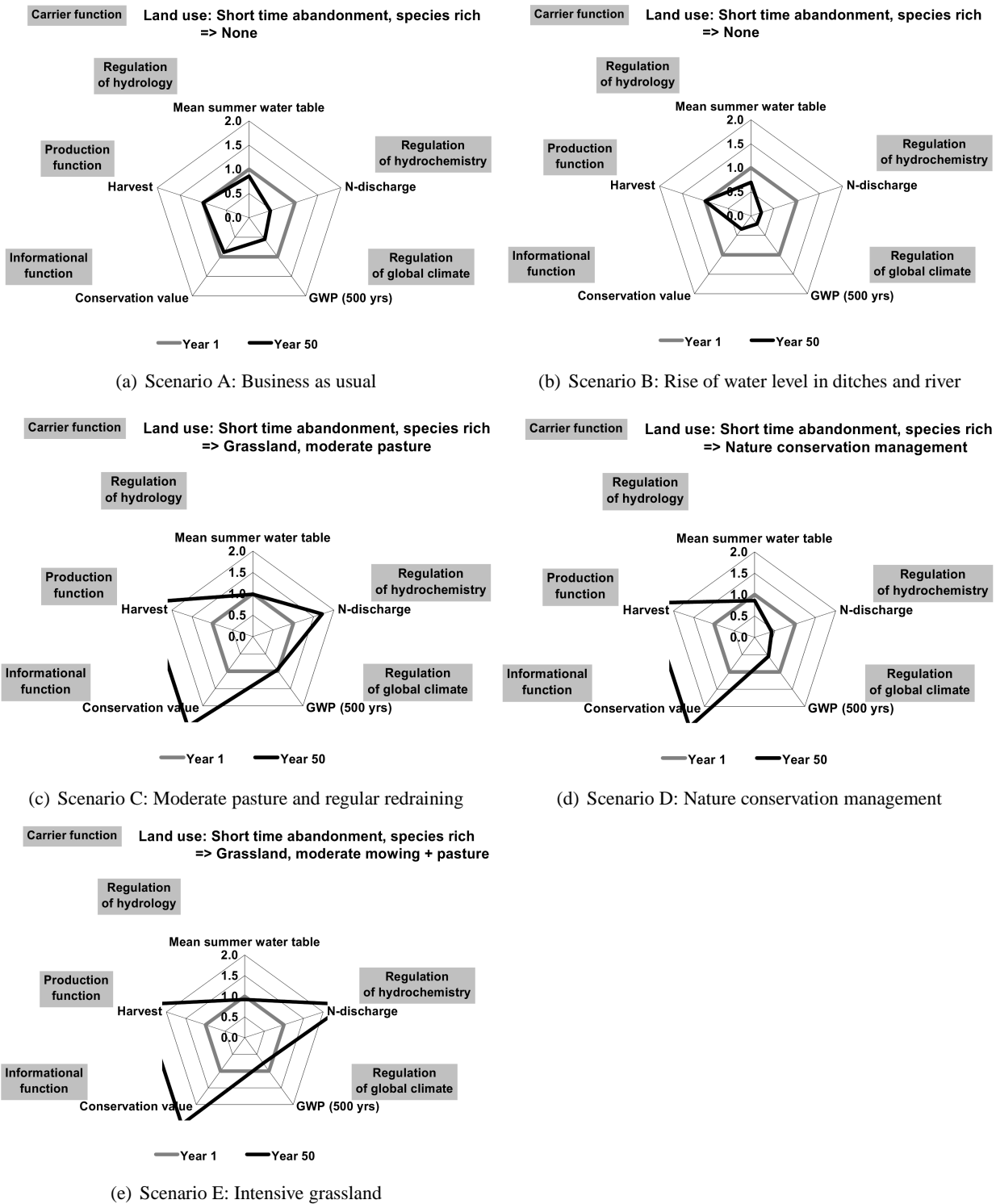


Figure 6.4: Results of land use and water management scenarios (A-E) for the discharge site in the Eider Valley, a minerotrophic peatland in northwest Germany. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line); the black lines show the relative changes of the indicators 50 years after the initial state (the maximum was set to 2.6).

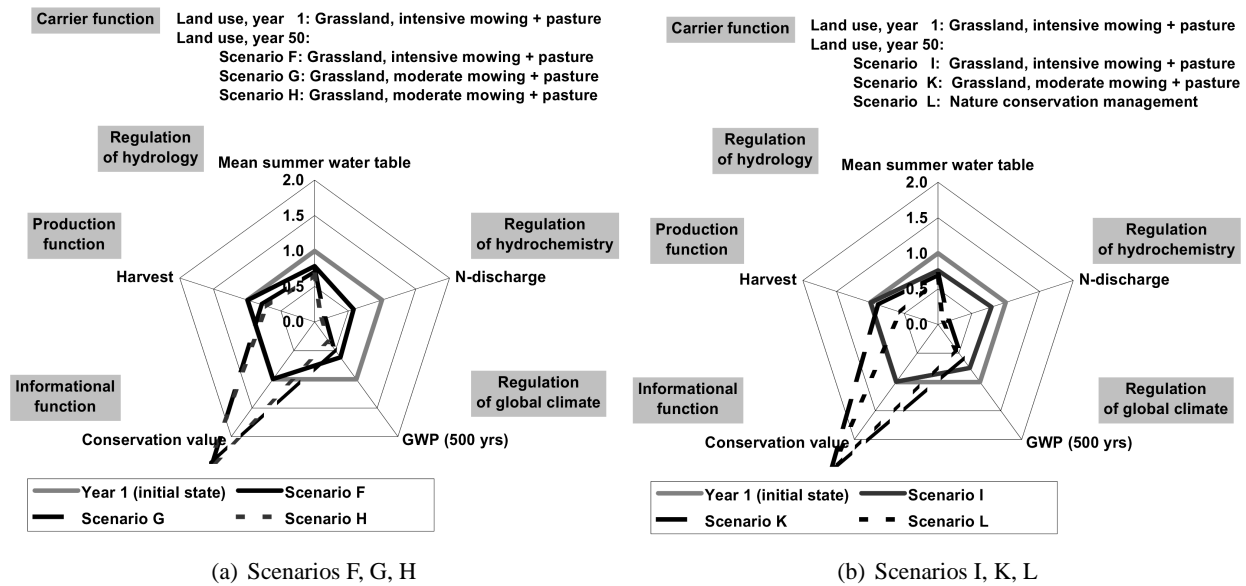


Figure 6.5: Results of the climate change scenarios (F-L) for the discharge site in the Eider Valley peatland. PMDSS output summarized in two amoeba diagrams: initial values of indicators were set to 1 (grey line); the continuous and discontinuous black lines show the relative changes of the indicators 50 years after the initial state (the maximum was set to 2.6).

Climate change scenarios

In all scenarios (F to L), the mean summer water table, N-discharge, and GWP_{500} are decreasing over time due to subsidence (figure 6.5). In scenarios F and G, land use remains 'intensive grassland' for 50 years; thus, also the harvest and the conservation value remain the same. At lower water tables, land use has changed to moderate grassland or nature conservation management after 50 years, resulting in a decrease of harvest and increase in conservation value.

In scenario F, depth to water table decreases due to subsidence as already described for scenario A, also resulting in a decrease of N-discharge and GWP_{500} (figure 6.5). Values for initial state as well as cumulative values after 50 years are considerably higher in difference to scenario A. As land use stays the same, the harvest and the conservation value remain the same as well. The changes of the depth to water table in scenarios G and H to 40 and 30 cm respectively lead to changes in land use after approximately 40 and 20 years respectively (compare figure 6.6), as certain water table levels are passed faster. With the change to moderately used grassland, the conservation value also increases. If a temperature increase is included in the otherwise identical conditions (scenarios I - L, figure 6.5 b), subsidence is enhanced. Due to higher mineralization rates, N-discharge and GWP are higher in scenario I than F. Land use change occurs faster at higher temperatures, as the depth to water table is decreasing faster (figure 6.6).

It can be concluded that climate change influences long-term development of peatland functions, because of the enhancement of the subsidence rate. With higher depths to water table and higher air temperatures, the land use category automatically changes faster if the site will not be redrained.

6 Case studies

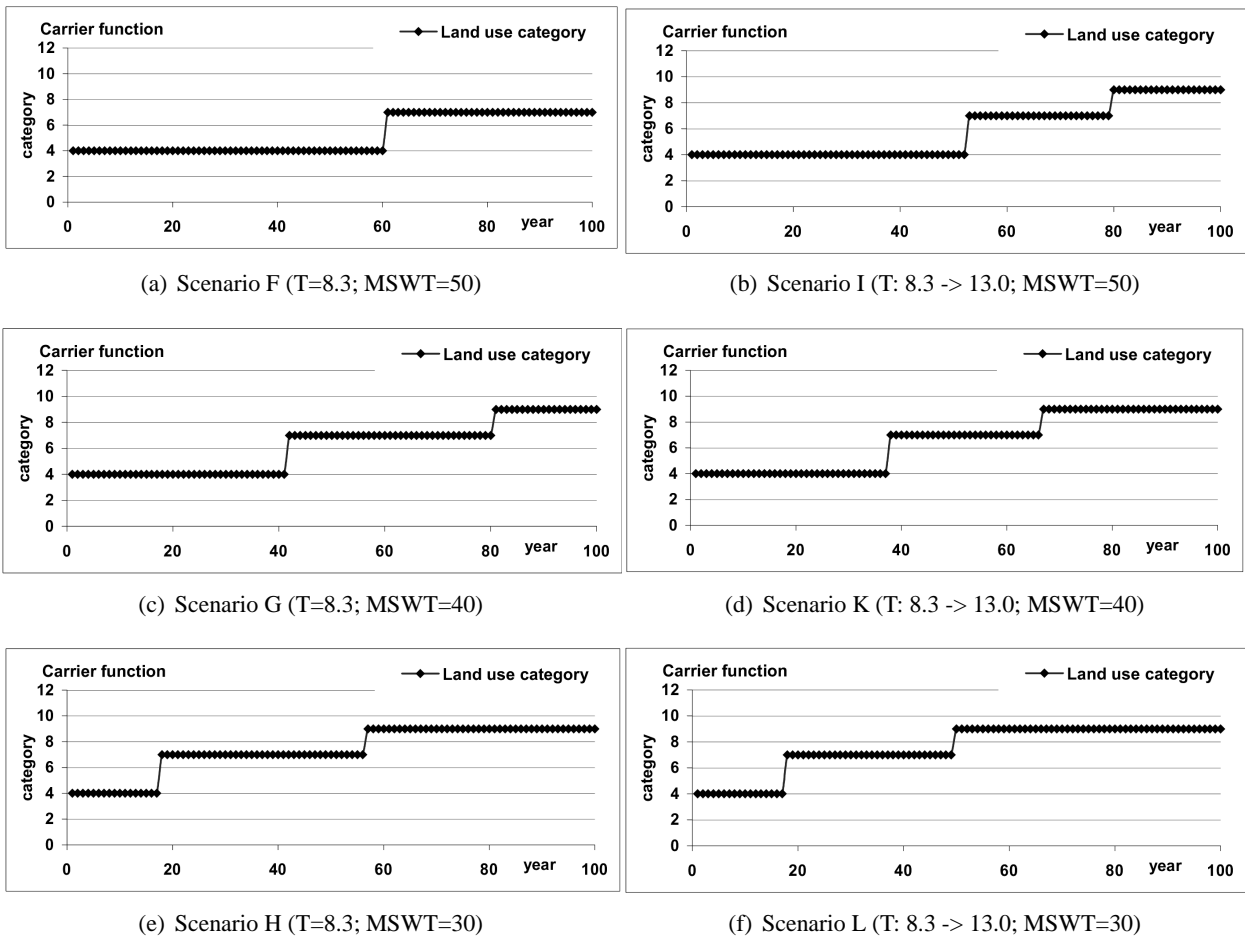


Figure 6.6: Results of the climate change scenarios for the discharge site in the Eider Valley peatland. PMDSS output of land use category as time series graphs. T: temperature [°C]; MSWT: mean summer water table of second model year [cm below surface]. T=8.3: temperature remains the same over 100 years; T=8.3->13.0: linear increase of temperature over 100 years. Land use categories are explained in table 5.3 on page 60.

6.1.5 Validation

The results achieved with PMDSS are plausible as a rough estimate of magnitude and development trend, according to the state of knowledge concerning peatlands (described in chapter 4).

As the calculation of subsidence rate in PMDSS is based on an empirical equation for deep peatlands in northeast Germany (equation 4.7 on page 19), the actual subsidence rates in the Eider Valley might be marginally lower than the calculated ones.

The modelled Global Warming Potentials correspond to measured ranges (table 4.10 on page 43). Calculated nitrogen discharge is within a realistic range and development trend (chapter 4.3.5.1 on page 43).

The harvest changes show the expected development and the values are comparable to the measurements and recommendations (table 4.6 on page 35).

Decrease of red list plant species due to abandonment (scenarios A and B) is in agreement with decrease in biodiversity in conjunction with secondary succession (WOŁEJKO 2002, SCHRAUTZER & JENSEN 1999, FOJT & HARDING 1995, ROSENTHAL 1992). The increase of the conservation value with starting moderate land use or nature conservation management (scenarios C, D and E) accounts for the potential habitat suitability of the site for red list plant species. The ability of rare plants to colonize the site depends on the seed bank of the site and on dispersal of plants from neighbouring sites (MAAS & SCHOPP-GUTH 1995, JENSEN 1998).

Land use changes from intensive to moderate grassland or to abandoned sites due to the fact that peatlands are getting wetter due to subsidence can be observed in Schleswig-Holstein (SCHRAUTZER & WIEBE 1993).

Concerning the climate change scenarios, PMDSS only accounts for higher microbial activity due to higher temperatures. This leads to higher mineralization rates and subsequent changes of the other functions. In contrast to the scenario results, higher temperatures may lead to an increase in evapotranspiration and thus to increasing depth to water tables in the summer (MOORE 2002, STRACK *et al.* 2006). On the other hand, the increasing precipitation in the given scenarios (table 6.4) may lower this effect. A subsequent decrease of the depth to water table as simulated may still occur, but with a different initial value. If the summers are getting warmer and dryer, the enhancement of mineralization and thus the trend of development of other function is plausible.

6.1.6 Discussion

Land use and water management scenarios

The scenario results show the effects of land use and water management on the development of ecosystem functions on the selected peatland site. Depending on the priority of the user, different scenarios may be evaluated differently. Beside the business as usual scenarios, it has to be considered that land use and water management changes result in different high costs for their realization (SCHOUWENAARS 2002).

As the site is getting wetter itself in the business as usual scenario (A), active rewetting (scenario B) enhances this development into the same direction (PRICE *et al.* 2003). The decrease of N-discharge and Global Warming Potential can be evaluated as positive. The insignificant change of the conservation value can be evaluated as neutral (scenario A) and the decrease as negative (scenario B). In the nature conservation scenario (D), all indicators develop into a direction. This can be evaluated as positive (e.g. increase of harvest and conservation value, decrease of N-discharge and GWP₅₀₀). Thus, this option could be a good compromise for the future use of the site with respect to all ecosystem functions.

The change to moderate (scenario C) or intensive grassland (scenario E) is an option if the focus is on the production function. The results of those scenarios show that sites have to be drained regularly to keep

the same land use. Due to continuous lowering of the surface level, drainage can get expensive and not worthwhile anymore, as already observed in northern Germany (SUCCOW 2001, TREPEL 2003). Those sites are either used more moderately as in scenario E or left abandoned. Negative effects of moderate and intensive grassland use and redrainage are permanently high N-discharge and Global Warming Potential values.

Climate change scenarios

The results of the climate change scenarios point out the effect of enhanced mineralization rates due to the effect of temperature increase on peatland functions. This is due to the construction of PMDSS, where temperature has direct effects on the calculation of the subsidence rate, CO₂-emission, CH₄-emission, and N-mineralization (chapter 4). Other effects - especially on hydrology - are not integrated in PMDSS. Thus, temperature increase leads to higher N-discharge and higher GWP₅₀₀. The higher subsidence rates with increasing temperature lead to a faster extensification of the sites if no effort of redrainage is made (figure 6.6). At deep drained sites, intensive land use is still possible for 50 years independent from temperature increase (scenarios F and I). A negative effect of the increase of subsidence rates due to climate change would be the faster decline of peat thickness.

The farmer may not follow the extensification sequence on peat soils. With increasing temperature, the farmer may have the choice to use the site less intensively at an earlier point of time or to redrain the site more often. Usually, the first choice results in lower income; the second choice results in higher drainage costs. Instead of using the sites less intensively, they are left abandoned if no option for further usage is worthwhile anymore.

6.2 The peatland Mötjerpolder, Germany

6.2.1 Purpose and motivation

On request of the nature conservation foundation 'Stiftung Naturschutz', the effects of the rewetting of the minerotrophic peatland Mötjerpolder on its peatland ecosystem functions was simulated with PMDSS. The special interest of the nature conservation foundation lies in the analysis of the effects of rewetting on the CO₂-emission and carbon sequestration of the Mötjerpolder.

The Mötjerpolder is a part of the lowland Lundener Niederung, situated in an Europe-wide important wetland in the state of Schleswig-Holstein, Germany. It is a 320 ha large former minerotrophic fen complex and now owned by the 'Stiftung Naturschutz'. The management aim for this area is the natural development to a fen. Therefore, the area was rewetted in 1998 and the land use was adopted to the new water levels. Furthermore, the Schleswig-Holstein state bank sponsored 279 000 DM (= 142 650 Euro) as compensation for operational CO₂-emissions (STIFTUNG NATURSCHUTZ SCHLESWIG HOLSTEIN 2000). The 'Prima Klima' society (English: good climate) estimated an annual carbon fixation of 1 600 t/a on a completely rewetted Mötjerpolder. An evaluation of the effects of the rewetting measurements on the development of the peatland and carbon fixation rates has not been planned yet. Monitoring data to evaluate the changes are scarce.

This chapter is an update of a report (KNISS *et al.* 2005). All scenarios have been simulated again with PMDSS version 1.14.

6.2.2 Site description and data basis

The input data for the decision support system PMDSS were elevated from planning reports, literature, and conversations with the foundation and during a site inspection.

Climate data

The mean long-term annual precipitation varies between 800 and 900 mm according to a precipitation map (MÜLLER-WESTERMEIER *et al.* 1999). The most nearby situated climate stations Erfde and Heide have mean annual precipitation rates of 819.9 and 894.9 mm/a respectively (MÜLLER-WESTERMEIER 1996).

The mean long-term annual air temperature is between 8.0 and 8.5°C according to a temperature map (MÜLLER-WESTERMEIER *et al.* 1999). The most nearby situated climate stations Erfde and Heide have mean annual air temperatures of 8.3°C (MÜLLER-WESTERMEIER 1996).

Surface shape

The soil surface of the Mötjerpolder lies completely below the sea level (between -1.4 and -0.1 m ASL) according to the topographical map DGK 5. The lowest point lies in the lake Mötjensee at -2 m ASL (ALR 1998).

Land use and vegetation before rewetting

The main part of the lowland Lundener Niederung was used as wet grassland (meadows and pastures) in the last centuries. It is assumed that this was also the situation at the higher parts of the Mötjerpolder. Concerning the whole Lundener Niederung (approximately 3500 ha) 80% grassland, 10% reed and 10% wood/ forest and abandoned land are assumed for land cover (ALR 1998).

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In 1991, an area of 1-3 ha of the lake Mötjensee was an open water surface (LN 1991). The central terrestrialization area of the lake was captured by a widespread species poor reed. In the main part of this area, reed was cut in winter. The marginal terrestrialization area and the terrestrialization part of the former small lake 'Kleiner Mötjensee' were used as intensive meadow and pasture. In those parts, mainly tall sedges, small sedges, and reed have developed. Parts of this area are abandoned since the 1980s (LN 1991). Furthermore, small alder forests can be found in the Mötjempolder.

Water tables before rewetting

At the end of the 1970s, the water table was lowered by 50 cm (LN 1991). It can be assumed that the water tables were 20 to 50 cm lower before rewetting compared to the situation after rewetting.

Water tables after rewetting

In 1998, rewetting of the Mötjempolder was started with damming and redirecting the runoff ditch; parts of the area were flooded. It is assumed that the area below -1.20 m ASL is permanently wet (ALR 1998). Above this contour line, the groundwater table lies between 15 cm below surface at the Eastern boundary and more than 1 m below surface at the Western boundary (own observation, 05.08.2005). The water table of the redirected runoff ditch is below -1.3 m ASL (ALR 1998).

Land use and vegetation after rewetting

It is assumed that the parts lying below -1.2 m ASL are abandoned the whole year long due to high water tables. The higher parts are not fertilized and used with the purpose of nature conservation (mowing). A part of the forests is preserved and some parts already died due to high water tables.

Peat thickness

According to HUMMEL & CORDES (1969), a 1 m thick layer of fen and carr peat was accumulated during the Subboreal. Next, an up to 2 m thick layer of transitional fen and bog peat developed. Lakes established among the bogs and were filled with organic gyttja, such as the lake Mötjensee. During the Subatlantic, mainly further fen peat was built in the surrounding of the Mötjempolder. Marine clay mainly deposited in the north of the Lundener Niederung. Thus, hardly any clay layers are expected in the Mötjempolder. Bog peat was largely mined in the area during the last century.

Profile 114 of cut E in HUMMEL & CORDES (1969) lies south of the Mötjempolder with the following order:

0.5 m	Landfill (clay/ silt)
1.5 m	Fen peat
1.0 m	Marine clay
0.3 m	Marine fine sand with thin clay layers, underneath sand

Own drillings (05.08.2005) near a ditch dam at the eastern border of the Mötjempolder showed 0.6 m peat and below clay.

6.2.3 PMDSS input

In table 6.7, the assumed land use, vegetation, and mean summer water tables for the Mötjempolder before and after rewetting are listed. They were derived from the data basis (previous chapter) and are the base for

Table 6.7: Assumed land use, vegetation, and mean summer water tables for PMDSS input (No. are the 6 simulated subareas).

Part		Before rewetting (1998)			After rewetting (2005)		
No.	Area [ha]	Land use	Vegetation	Summer water table [cm below surface]	Land use	(Potential) vegetation	Summer water table [cm below surface]
1	2	None	Open water	max. -50	None	Open water	max. -80
1	38	Reed use	Reed	< 5	None	Reed	< 0
2	60	Moderate grassland	Wet meadow	> 10	None	Reed	≤ 0
3	10	Forest/ none	Wood	> 10	None	Reed	≤ 0
4	50	Moderate grassland	Wet meadow	> 10	Nature conservation ^a	Small sedges	> 5
5	10	Forest/ none	Wood	> 20	None	Wood	> 20
6	150	Moderate grassland	Wet meadow	> 30	Nature conservation ^a	Small sedges	15 to 100

^aNature conservation stands here for mowing with < 1 cut a⁻¹

the simulation.

For the PMDSS simulation, the following 6 subareas are distinguished (column 'No.' in table 6.7):

1. Reed
2. Wet meadow to reed
3. Wood to reed
4. Wet meadow to small sedges, high water tables
5. Wood
6. Wet meadow to small sedges, low water tables

Input parameters for PMDSS were derived from table 6.7. Input parameters which apply for all simulation runs are listed in table 6.8. The other input parameters, which differ between the different subareas, are listed in table 6.9. For the simulation with PMDSS, the parameters for the state before rewetting are entered in the column 'Initial state' and for the state after rewetting into column 'Change'. Thus, the situation of 1998 is equal to model year one and the situation of 2005 to second model year. This is because PMDSS was designed to be able to change most parameters only in the second model year and not later.

Table 6.8: PMDSS input for parameters which are the same for all subareas in the Mötjerpolder.

Parameter	Unit	Initial state	Change
Site Name	-	Mötjerpolder	
Impermeable layer below the peat ?	yes=1, no=0	1	
Air temperature	°C	8.3 ^a	
N-Deposition	kg N ha ⁻¹ a ⁻¹	28 ^a	
Water source	1, 5, 10	5	5
Field crop	grain, maize, forest, others	others	others
Country	G, N, NL, PL, SW, UK	G ^b	
Precipitation	mm a ⁻¹	830	
N-Deposition	mg N l ⁻¹	1.7 ^a	
Dying biomass after rewetting	kg N ha ⁻¹ a ⁻¹	0	0

^aStandard value of PMDSS^bG=Germany

Table 6.9: PMDSS input for parameters of subarea 1 to 6 in the Mötjerpolder.

Column	Parameter	Unit	Subarea					
			1	2	3	4	5	6
Initial state								
	Area	ha	40	60	10	50	10	150
	Peat thickness	m	0.5	0.5	0.5	0.8	0.8	0.8
	Clay layer near surface	m	0	0	0	0.05	0.05	0.05
	Land use number ^a	1 to 12	12	7	2	7	12	7
	Surface level	m ASL	-1.40	-1.10	-1.10	-0.80	-0.80	-0.50
	Lowest possible water table	m ASL	-2.50	-2.50	-2.50	-2.50	-2.50	-2.50
	Mean summer water table	cm below surface	-10	20	20	40	40	70
	Water table fluctuation	cm	15	20	20	20	20	30
	N-Fertilizer	kg N ha ⁻¹ a ⁻¹	0	0	0	0	0	60
Change								
	Land use number	1 to 12	12	12	12	9	12	9
	Lowest possible water table	m ASL	-1.50	-1.50	-1.50	-1.50	-1.50	-1.50
	Mean summer water table	cm below surface	-20	0	0	20	20	50
	Water table fluctuation	cm	15	10	10	20	20	30
	N-Fertilizer	kg N ha ⁻¹ a ⁻¹	0	0	0	0	0	0

^aLand use numbers: 2 = forest, 7 = moderate grassland, mowing+pasture, 9 = nature conservation management, 12 = none

6.2.4 PMDSS results

Change of peatland ecosystem functions over time

PMDSS output of change of peatland ecosystem functions are given as time series for each subarea (figure 6.7 to 6.12). In accordance with the input, mean summer water tables are rising in the second model year in all subareas. For subarea 1, it is simulated that the surface level is rising due to peat growth, as water table is above the surface. The difference between water surface and surface level is decreasing slowly with time. After rewetting depth to water table is not further changing on subarea 2 and 3. In this case, peat growth and rising surface level are simulated 10 years after rewetting. On subarea 4, 5, and 6 a rise of the water table results in an increase of the water table. However, subsidence is not stopped and leads to a further decrease of the depth to mean summer water table. The rates of the water table decrease are higher at subarea 6 than subareas 4 and 5.

At subarea 1 N-discharge stays very low all the time. At subareas 2 to 6, there is a rapid decrease in N-discharge in the second model year, followed by a further general decrease with time. The wetter the sites, the lower is the nitrogen discharge from the sites. For subarea 6, by far the highest N-discharge rates were modelled with $170 \text{ ha}^{-1}\text{a}^{-1}$ in initial state and 83 to $20 \text{ ha}^{-1}\text{a}^{-1}$ after rewetting.

In subareas 1, the GWPs remain at the same level. Short-term and mid-term GWPs (GWP_{20} and GWP_{100}) are much higher than the long-term GWP (GWP_{500}). At subarea 2 and 3, the three different GWPs are at the same level. In the second model year and later, they show the same behaviour at subarea 1. GWP_{20} is increasing, GWP_{100} remains the same and GWP_{500} is decreasing in the second model year. At the dry subareas 4, 5, and 6, the GWPs of the different time horizons are initially nearly the same. They are rapidly decreasing during the second model year and later smoothly further decreasing. At subarea 4 and 5, GWP_{20} is increasing after some decades, while GWP_{100} and GWP_{500} are further decreasing. At subarea 6, GWP_{20} and GWP_{100} are marginally higher than GWP_{500} in the first years.

Land use categories are changing in the second model year to less intensive categories, according to the input. No further land use change is modelled over the next 100 years.

Harvest is changing as expected according to the land use types. At subarea 1, there is no harvest. At subareas 2, 3, and 5, harvest is stopped after rewetting. At subareas 4 and 6, harvest is on the whole continuously decreasing.

The conservation value stays low in subarea 1. The conservation values of subareas 2 to 6 are medium at the initial state. In subarea 2 the conservation value is decreasing to a low value. In subarea 3, the change is insignificant although the text output gives a low value for the 50th year. At subareas 4 and 6, the conservation value is increasing to a high value. At subarea 5, the conservation value remains. At subareas 3 and 5, which have wood in initial state, PMDSS gives the further text output: 'some vegetation communities protected by the FFH directive'.

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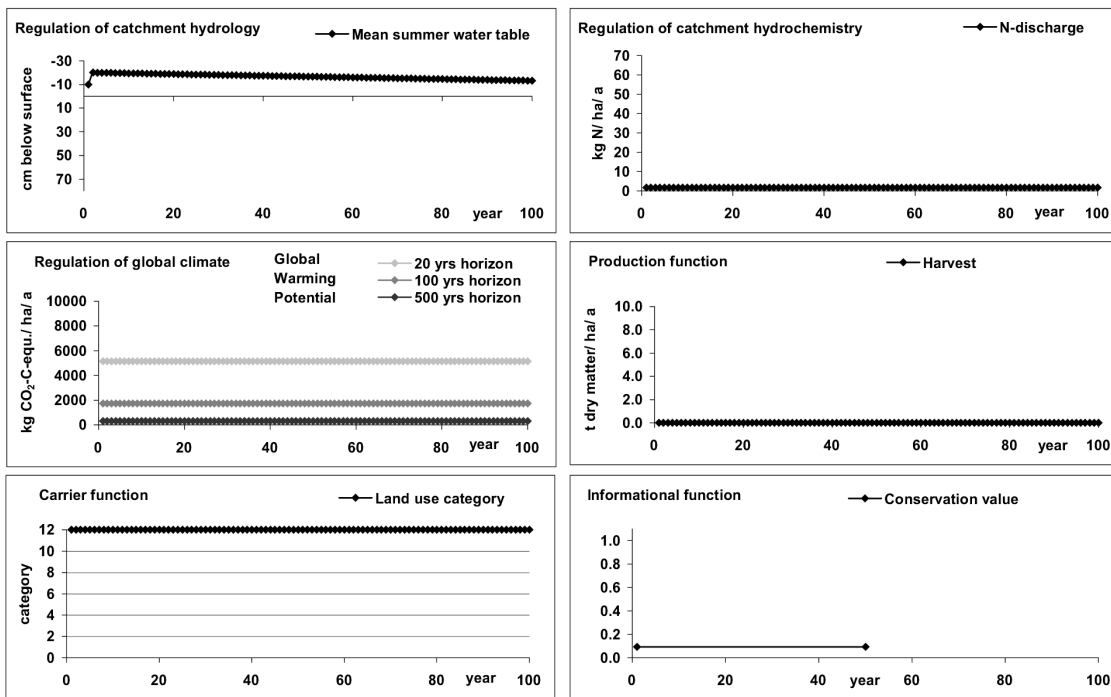


Figure 6.7: PMDSS output: development of peatland ecosystem functions at subarea 1 (reed).

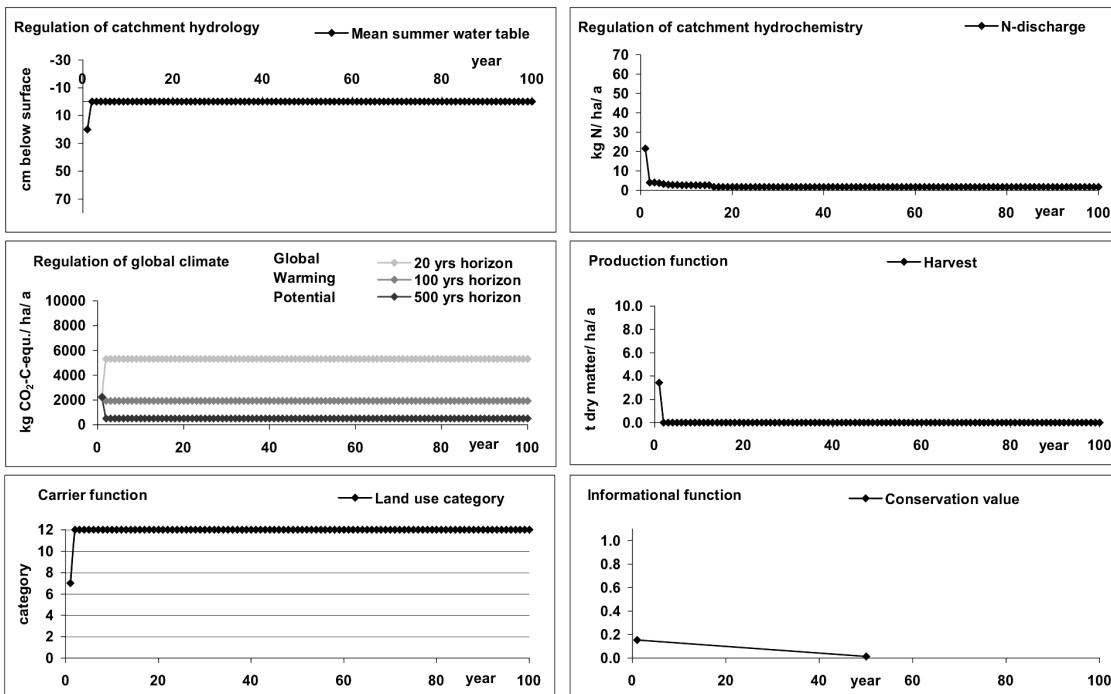


Figure 6.8: PMDSS output: development of peatland ecosystem functions at subarea 2 (wet meadow to reed).

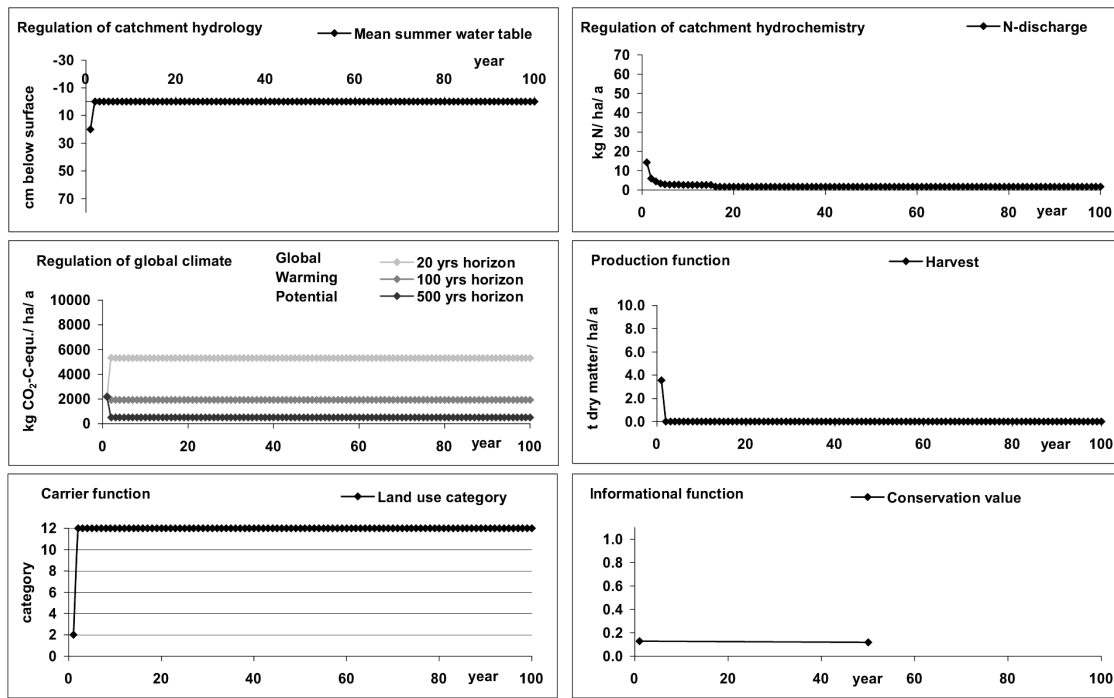


Figure 6.9: PMDSS output: development of peatland ecosystem functions at subarea 3 (wood to reed).

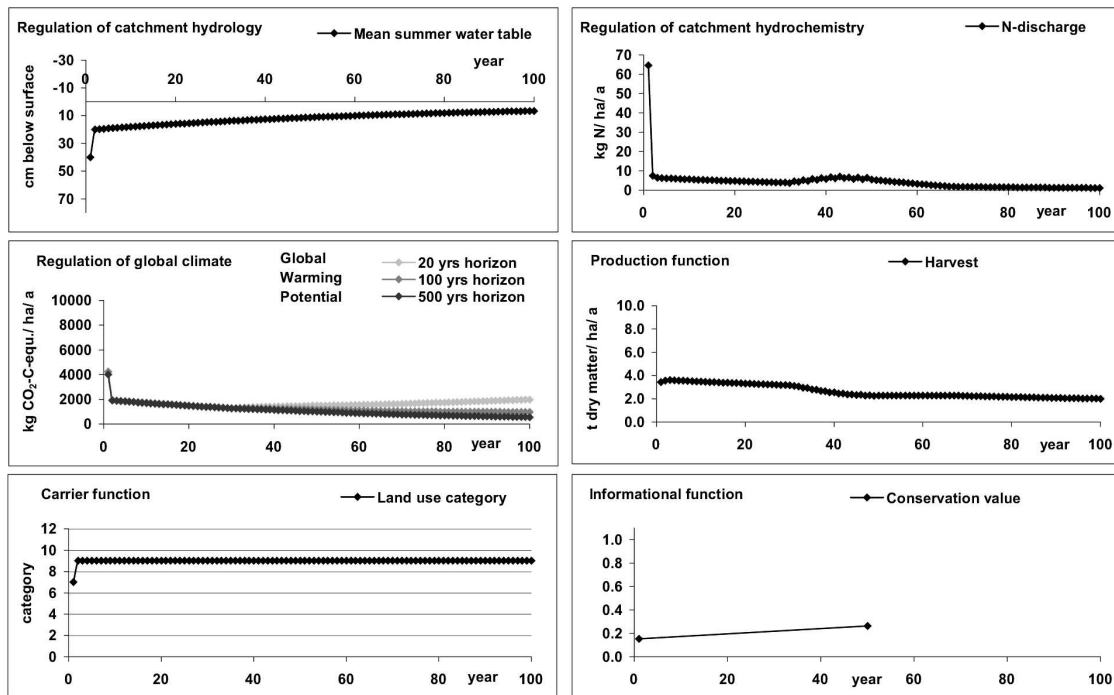


Figure 6.10: PMDSS output: development of peatland ecosystem functions at subarea 4 (wet meadow to small sedges, high water tables).

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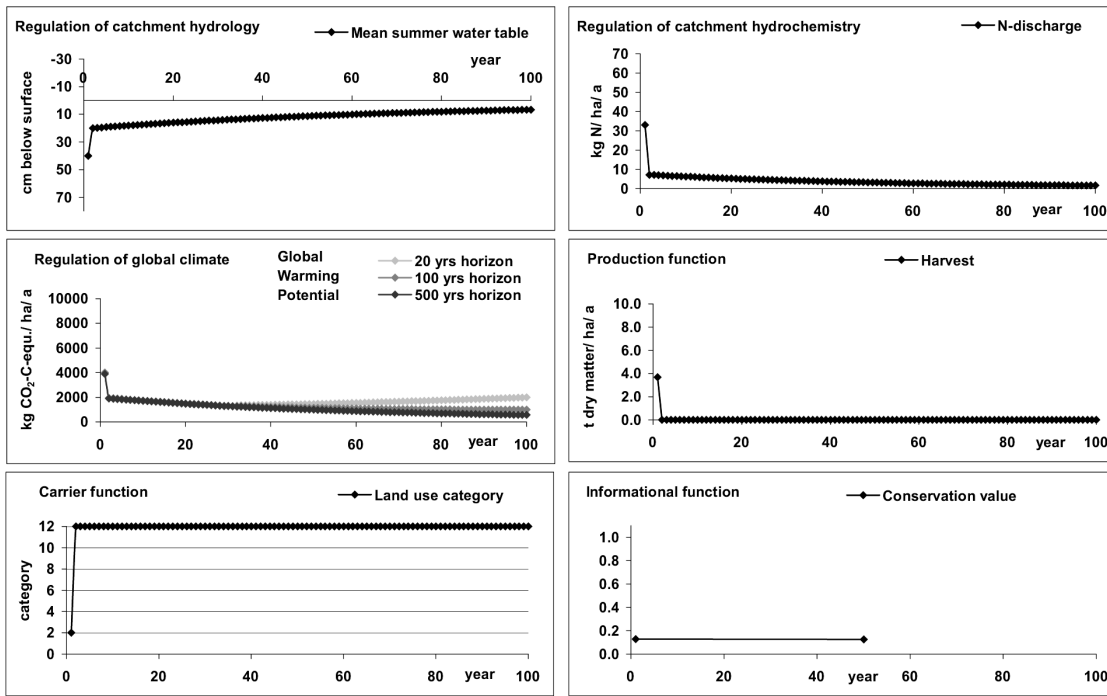


Figure 6.11: PMDSS output: development of peatland ecosystem functions at subarea 5 (wood).

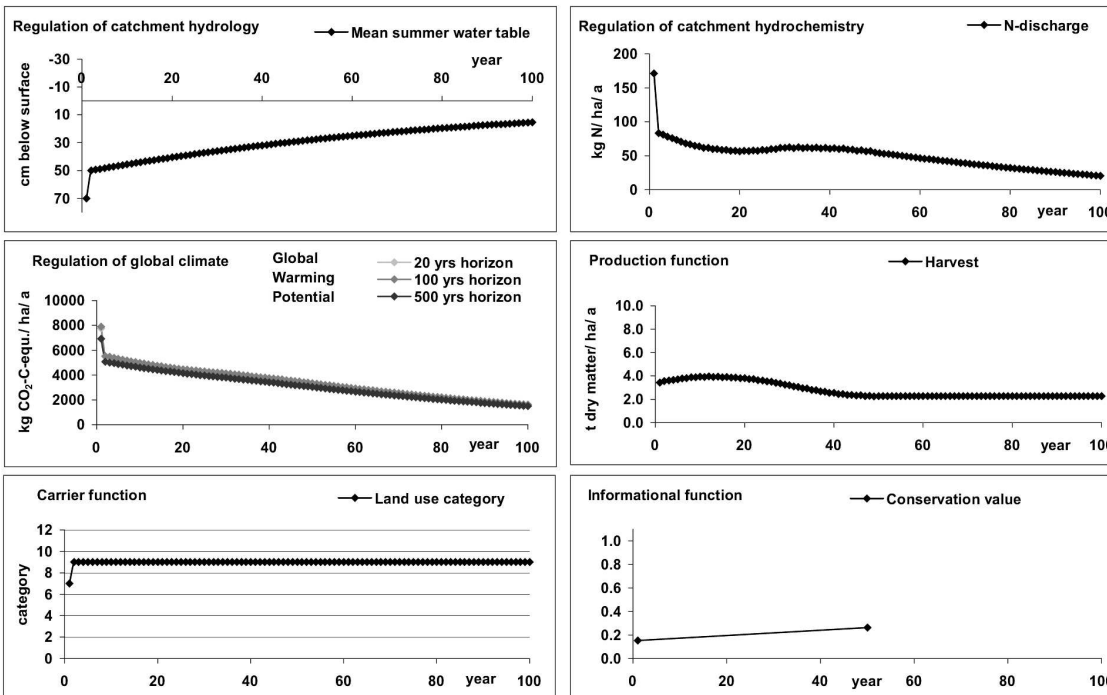


Figure 6.12: PMDSS output: development of peatland ecosystem functions at subarea 6 (wet meadow to small sedges, low water tables).

Relative change of the peatland ecosystem functions after 50 years compared to the state before rewetting

The relative change of peatland ecosystem functions after 50 years in comparison to the initial state is presented in amoeba diagrams. For the amoeba diagram of the whole Mötjerpolder (figure 6.13), the indicators were either summed up (harvest, N-discharge, GWP₅₀₀) or area weighted mean values were generated (mean summer water table, conservation value). In the Mötjerpolder, rewetting has an effect on all other functions (figure 6.13). The conservation value increases by approximately 30%. GWP₅₀₀ and N-discharge will be more than halved. The harvest is going down by 50%. The separate view of the different subareas of the Mötjerpolder shows the different development of the peatland ecosystem functions of each subarea (figure 6.14). They represent the same results as described in the last paragraph in a different format (figures 6.7 to 6.12).

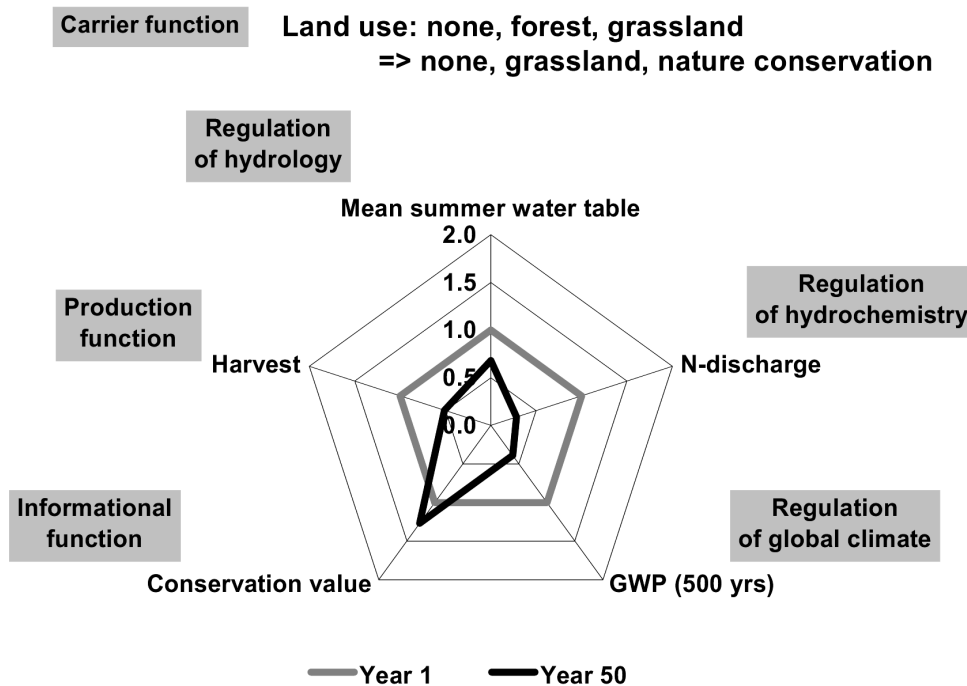


Figure 6.13: PMDSS output: relative change of peatland ecosystem functions of the whole Mötjerpolder after 50 years in relation to the state before rewetting. Values of initial state were set to 1 (grey line); the black line show the relative change of the indicators 50 years after the initial state (the maximum was set to 2.6).

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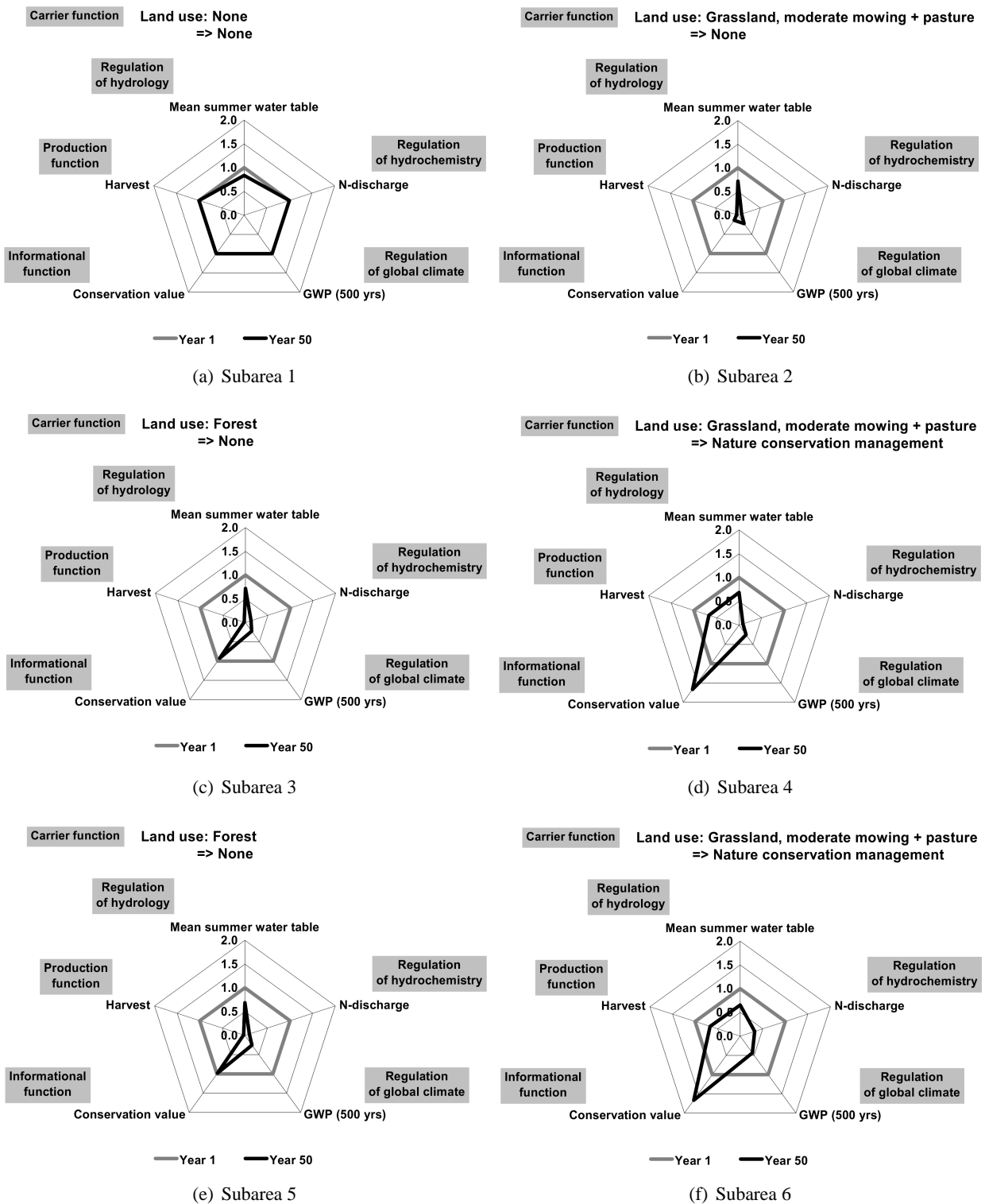


Figure 6.14: PMDSS output: relative change of peatland ecosystem functions of the subareas of Mötjenspolder after 50 years in relation to the state before rewetting. Values of initial state were set to 1 (grey line); the black line show the relative change of the indicators 50 years after the initial state (the maximum was set to 2.6).

Greenhouse gas emissions

Greenhouse gas emissions and GWPs are of special interest for the nature conservation foundation. The model results suggest that CO₂-emission and N₂O-emission of the whole Mötjerpolder are decreasing and CH₄-emission is increasing (table 6.10). GWP₁₀₀ of the Mötjerpolder area does decrease from 1664 t to 1150 t CO₂-C equ. a⁻¹ by 515 t due to rewetting. The model results suggest that due to further subsidence, GWP₁₀₀ will decrease during the next 50 years to 706 t CO₂-C equ. a⁻¹ by 444 t. Thus, during the 50 years after the initial state, GWP₁₀₀ decreases by 958 t CO₂-C equ. a⁻¹. The decrease of GWP₅₀₀ within 50 years after the initial state is similar with 919 t CO₂-C equ. a⁻¹ and that of GWP₂₀ lower with 697 t CO₂-C equ. a⁻¹ in comparison to GWP₁₀₀.

The different subareas contribute differently to the greenhouse gas emission and GWPs of the whole Mötjerpolder (table 6.11). Subarea 6 is contributing most to CO₂-emission with 878 t C a⁻¹ at the initial state, as it is the largest subarea with 150 ha and additionally most deeply drained both before and after rewetting. Correspondingly, the GWPs are highest at subarea 6 (e.g. GWP₁₀₀ is 1183 t CO₂-C equ. a⁻¹) and their reduction due to rewetting, too (e.g. GWP₁₀₀ is decreasing by 354 t CO₂-C equ. a⁻¹ due to rewetting). Also, subarea 2 and 4 contribute to considerable reduction of CO₂-emission by 134 and 95 t C a⁻¹ with rewetting. Subareas 1 and 2 contribute most to CH₄-emission (10 and 14 t C a⁻¹ respectively), whereas at subarea 2 only from model year 2 onwards. Increasing CH₄-emissions at subareas 2 and 3 lead to an increasing GWP₂₀ (183 and 31 t CO₂-C equ. a⁻¹). On all other subareas, GWP₂₀ is decreasing. GWP₁₀₀ and GWP₅₀₀ are decreasing at all subareas. N₂O-emission is decreasing at all subareas besides subarea 1, where it is zero all the time. Highest N₂O-emission rates were simulated for subarea 6 with 2.4 t N a⁻¹.

Table 6.10: PMDSS output: balance of greenhouse gas emissions and GWPs in the whole Mötjerpolder of before rewetting (initial state), after rewetting (change), and 50 years later.

Parameter Unit	CO ₂ t C a ⁻¹	CH ₄ t C a ⁻¹	N ₂ O t N a ⁻¹	GWP ₂₀	GWP ₁₀₀	GWP ₅₀₀
				t CO ₂ -C equ. a ⁻¹		
Initial state	1240	10	2.7	1776	1664	1444
Change	774	27	1.22	1513	1150	920
After 50 years	438	28	0.27	1096	706	525
Difference change - initial state	-466	+17	-1.48	-263	-515	-524
Difference after 50 years - change	-336	+1	-0.95	-416	-444	-395
Difference after 50 years - initial state	-802	+18	-2.43	-697	-958	-919

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Table 6.11: PMDSS output: balance of greenhouse gas emission and GWPs on subareas in the Mötjerpolder before rewetting and 50 years later.

Sub-area ^a	Parameter Unit	CO ₂ t C a ⁻¹	CH ₄ t C a ⁻¹	N ₂ O t N a ⁻¹	GWP ₂₀ t CO ₂ -C equ. a ⁻¹	GWP ₁₀₀	GWP ₅₀₀
1 (40 ha)	Initial state	-12	10	0	206	70	12
	Change	-12	10	0	206	70	12
	After 50 years	-12	10	0	206	70	12
	Difference change - initial state	0	0	0	0	0	0
	Difference after 50 years - change	0	0	0	0	0	0
2 (60 ha)	Initial state	126	0	0.06	136	137	132
	Change	-7	14	0.01	319	115	29
	After 50 years	-7	14	0	319	115	29
	Difference change - initial state	-134	+14	-0.05	+183	-21	-102
	Difference after 50 years - change	0	0	0	0	0	0
3 (10 ha)	Initial state	21	0	0.01	22	22	22
	Change	-1	2	0	53	19	5
	After 50 years	-1	2	0	53	19	5
	Difference change - initial state	-22	+2	-0.01	+31	-3	-17
	Difference after 50 years - change	0	0	0	0	0	0
4 (50 ha)	Initial state	187	0	0.20	211	213	201
	Change	92	0	0.04	97	97	95
	After 50 years	45	1	0.01	73	57	49
	Difference change - initial state	-95	0	-0.17	-114	-116	-106
	Difference after 50 years - change	-47	+1	-0.02	-24	-40	-46
5 (10 ha)	Initial state	39	0	0.02	40	40	39
	Change	21	0	0.01	19	19	19
	After 50 years	11	0.32	0	15	11	10
	Difference change - initial state	-18	0	-0.01	-20	-21	-20
	Difference after 50 years - change	-10	+0.32	0	-5	-8	-9
6 (150 ha)	Initial state	878	0	2.40	1162	1183	1039
	Change	681	0	1.16	819	829	759
	After 50 years	403	0	0.25	432	434	419
	Difference change - initial state	-197	0	-1.24	-343	-354	-280
	Difference after 50 years - change	-279	0	-0.92	-387	-395	-340

^aSubareas: 1 = reed; 2 = wet meadow to; 3 = wood to reed; 4 = wet meadow to small sedges, high water tables; 5 = wood; 6 = wet meadow to small sedges, low water tables

Table 6.12: Modelled greenhouse gas emission rates of the Mötjerpolder (per hectare and year).

Parameter Unit	CO ₂ kg C ha ⁻¹ a ⁻¹	CH ₄ kg C ha ⁻¹ a ⁻¹	N ₂ O kg N ha ⁻¹ a ⁻¹	GWP ₂₀ kg CO ₂ -C equ. ha ⁻¹ a ⁻¹	GWP ₁₀₀	GWP ₅₀₀
Initial state	3875	30	8	5549	5201	4513
After 50 years	1369	87	1	3427	2206	1640

6.2.5 Validation

Peat growth and subsidence of soil surface

For subarea 1, 2, and 3, peat growth was simulated as expected from model equations. This simulation reflects plausible sedimentation of organic material in the reed. Simulated subsidence rates of subareas 4, 5, and 6 vary with the mean summer water table. At subarea 6, subsidence range from 0.72 (initial state) to 0.18 cm a⁻¹ (year 100). At subareas 4 and 5, subsidence rates range from 0.47 (initial state) to 0.06 m a⁻¹ (year 100). The results are comparable with subsidence rates calculated with the equations of BLANKENBURG *et al.* (2001) (equations 4.4 and 4.5): 0.86 to 0.08 cm a⁻¹ for subarea 6 and 0.43 to -0.02 cm a⁻¹ for subareas 4 and 5. The negative value accounts for peat growth which was not simulated with PMDSS for subareas 4 and 5. Subsidence rates within the same order of magnitude are reported for Germany in the literature (HENNING & HOHMANN 2000, MUNDEL 1976, compare table 4.2 on page 17).

Nitrogen discharge

The results for N-discharge are as expected from model equations. With decreasing depth to water table, N-discharge is decreasing due to decreasing mineralization rates. In addition to mineralization, fertilization is contributing to high N-discharge at the initial state of subarea 6. An N-discharge rate of 170 kg ha⁻¹ a⁻¹ appears to be too high for moderate grassland. In the model, high losses are caused by high mineralization rates. The other N-discharge values of all subareas are between 1 and 83 and within a plausible range (TREPPEL 2000, chapter 4.3.1.1 on page 16).

Greenhouse gas emission and GWP

Model results of greenhouse gas emission rates and Global Warming Potentials are within measured values in Germany and Europe, compare table 6.12 and 4.10 on page 43 (BYRNE *et al.* 2004, AUGUSTIN 2001, MEYER *et al.* 2001). Concerning table 4.10, parts of the Mötjerpolder belong to the categories 'rewetted' and 'restoration' and other parts to 'drained'. Before rewetting, approximately 1/8 of the Mötjerpolder was wet and 7/8 drained and after rewetting approximately 1/3 was wet and 2/3 drained.

Vegetation development and conservation value

Initial state conservation values are used in PMDSS according to the calculated conservation values of the standard levees. Thus they reflect average values of the majority within each vegetation group (HOLSTEN 2006). Changes of conservation values 50 years later correspond to the order of those values, but are not equal.

The conservation value of reed is low in the model runs (subareas 1, 2, 3). A comparison with a red list for vegetation groups developed in the state Schleswig-Holstein (DIERSSEN *et al.* 1988) allows an evaluation of this model results. Four plant groups have been classified to be not endangered (*Glycerietum maximae*, *Sparganietum erecti*, *Acoretum calami*, *Glycerio-Sparganietum neglecti*) and two were classified endangered (*Schoenoplecto - Phragmitetum australis*, *Cicuto-Caricetum pseudocyperi*). Further plant groups of reed are usually found on different subsoils than peat soils.

The development of reed after flooding a wet meadow, as simulated for subarea 2, was described by GROOTJANS *et al.* (2002).

For subarea 3, simulation results predict a vegetation succession from wood to reed due to a rising water table. This is in accordance with the description by LAMERS *et al.* (2002): at constant water tables near soil surface, groves were dying out. A development of alder carrs at high summer water tables (between 12 cm above and 6 cm below surface) could be possible too (ALNUS-FORSCHUNG 2005). In 2005, dead trees could be observed in the peatland Mötjerpolder.

A vegetation change from wood to reed due to rising water table was modelled for subarea 3. Contrariwise, it is stated in the literature that alder carrs may still occur at summer water tables between 12 cm above and 6 cm below surface (ALNUS-FORSCHUNG 2005). A extinction of groves at constant water tables near soil surface was described by LAMERS *et al.* (2002). Low water table fluctuations are especially important to let groves die in alder forest at a constant rise of the water table to soil surface level. After the dying of the alder trees, reed species are spreading. Some dead trees have already been observed in 2005 by the author.

At subareas 4 and 6, the succession of wet meadow to small sedges is simulated in connection with an increasing conservation value. This is in accordance with decreasing standing crop production observed on a previously fertilized area in the Netherlands which was mown without fertilizing for 14 years (OLFF & BAKKER 1991). The species number decreased during the investigations, but an increase in endangered species could not be observed. The increase in the nature conservation value has to be interpreted as an increase in habitat suitability for red list species. If these species are really coming depends on the seed bank of the site or the existence of the species nearby and possible dispersal vectors. If rare species have no possibility to reach the site, the nature conservation value can be overestimated with the model.

Land use and harvest

Land use change is in accordance with the input data. Harvest decrease at the subareas is in accordance with land use change (extensification) and water table rise as to be expected.

6.2.6 Discussion

With PMDSS, the development trend of the ecosystem functions of the peatland Mötjerpolder could be demonstrated. Despite the imprecise data basis and roughly estimated input data (such as area, land use, vegetation, peat thickness, water tables), reasonable results could be achieved. The rewetting of the Mötjerpolder is leading to a decrease in N-discharge, GWP₅₀₀, harvest, and decreasing depth to water table. The conservation value is increasing (figure 6.13). Land use categories are changing to less intensive ones, where 120 ha are left abandoned and 200 ha are managed for the purpose of nature conservation.

This development can be evaluated as positive regarding climate change, eutrophication of rivers and lakes, and preservation of biodiversity. As the production function has a low priority for the nature conservation foundation at this site, the decrease of harvest is not important. Looking into detail, there are some negative aspects concerning this predicted development trend, because the management target of the Mötjerpolder is the natural development to a fen. Peat growth was simulated only for 110 ha (subareas with summer water tables at the surface or above), thus no peat growth is simulated for 210 ha. To reach the aim of fen development, further rewetting measures are necessary to increase water tables. This would result in a complete stop of land use, no harvest, decrease in conservation value and in a higher decrease of N-discharge and GWP. However, different authors suggest that further use of alder or reed on growing fens might be possible (DUENE E.V. 2005, TIMMERMANN *et al.* 2003). However, establishing "wild" areas in a cultural landscape may be valuable by itself.

This raises the discussion about the negative effect of rising the water tables to surface on the conservation value. The conservation value just regards the red list plant species. For animals (especially birds), reed stands might be valuable. Also few reed stands are classified as endangered. Moreover, it is worthwhile to preserve entire ecosystems. Furthermore, it has to be considered that the conservation value is just a potential for red list plant species to reach this site. This will depend on seed banks, plant dispersal, and abiotic conditions of the site. If enough money is available, rare plant species can also be introduced if habitat conditions are suitable.

The model results show also that drained sites are getting wetter not only due to rewetting but also due to subsidence thereafter. Thus, in the amoeba diagrams and time series graphs, subsidence leads to a decrease of GWP₅₀₀ and N-discharge, which visually has a positive effect. Yet, looking at absolute numbers, one has to consider that due to mineralization, GWP₅₀₀ and N-discharge are still higher than without subsidence. More, subsidence has a high negatively effect on reducing peat thickness at the thin peat layers at the Mötjerpolder. At subarea 6, peat thickness will decrease from 80 to 45 cm within next 100 years. At subareas 4 and 5, peat thickness will decrease by 14 cm to 66 cm. Yet, as the starting value is only an estimated mean value, areas with even less peat thickness may extinct.

The special interest in the state bank of the state Schleswig-Holstein is carbon uptake. This develops as follows. It can be assumed that some subareas (1, 2, 3) sequester carbon dioxide. As not the whole area was rewetted, the Mötjerpolder acts still as a CO₂ source after rewetting. Based on PMDSS results CO₂-emission after rewetting is approximately 470 t/a less than before rewetting and GWP₅₀₀ about 520 t CO₂-C equ./a less (table 6.10). 50 years later, GWP₅₀₀ is reduced by about 920 t CO₂-C equ./a in relation to the situation before rewetting. In relation to these results, the aim of carbon uptake of 1600 t/a will not be achieved. Yet, the range of literature values in table 4.10 on page 43 shows that a decrease of CO₂-emission or Global Warming Potential can be clearly lower or higher. More precise information about the greenhouse emission rates and the change of GWPs is only possible with measurements on site.

With PMDSS, the effects of rewetting measures on the peatland functions of the Mötjerpolder were shown. Realistic management aims were identified. To estimate the effect of the rewetting of the Mötjerpolder more precisely, further investigations are necessary. For evaluating the potential development of the wet parts to a growing fen, factors such as degradation of the soil, settlement of plants, hydrological regime, and climate play a role. Thus, regular mapping of biotope types and regular measurements of water tables are recommended.

6.3 Sites of EUROPEAT partner countries

6.3.1 Introduction

One objective in the Europeat project was the "determination of the effects of land use and water management and global climate change on the deterioration and restoration of selected peat soils on the field, regional and European scale". This chapter contributes to this aim and is in addition a test of the decision support system for peatland management (PMDSS).

Objectives of this chapter are:

- to determine the effects of land use and water management and global climate change on the development of ecosystem functions of peatlands,
- to assess if PMDSS is applicable at the peatland sites of the project partners, and
- to evaluate the userfriendliness and understandability of PMDSS

A questionnaire was sent to the project partners (Annex D). Within the EUROPEAT project, every project partner had several peatland sites for investigations (chapter 3.1). The project partners had to apply PMDSS to their peatland sites and simulate different scenarios. In the questionnaire, it was asked for presentation of the results, description of the validity of the results, and feedback about the advantages and disadvantages of the model and its userfriendliness. The model PMDSS and its documentation were available for the project partners at the web page of PMDSS: <http://www.ecology.uni-kiel.de/~akniess/PMDSS>. Furthermore, they took part in a one-day introductory course to a previous version of PMDSS. The questionnaire was completed by four project partners including Germany (table 6.13). Thus, the stakeholders in this case are researchers who are experts in abiotic conditions on peat soils. Help was provided for using PMDSS and simulating the scenarios. Thus, there already was feedback of the users during the modelling process. Due to the requests, a number of bugs were removed and the project partners received help with the application and adjustment of PMDSS to their sites. For completing the questionnaires, the project partners in the Netherlands, Sweden and Norway used the model versions 1.02 to 1.04. All scenarios were simulated again with version 1.14 for this chapter. A few changes were made in the input in comparison to answers of questionnaires (those are indicated). The simulation for the German sites (with model version 1.14) is reported in length in chapter 6.1. A summary of input and results is given in the following sections. Sections 6.3.2 to 6.3.7 are mainly based on the answers by project partners (update of the report KNISS & TREPEL 2006). Afterwards, the results are discussed in section 6.3.8, referring to the objectives.

6.3.2 Site descriptions

A short site description of the peatland sites was given by the project partners as summarized below.

Table 6.13: Countries, sites, and authors who completed the questionnaire.

Country	Site(s)	Author(s)
Netherlands	Zegveld-Parcelnr. 3 and Zegveld-Parcelnr. 13	Ria Wolleswinkel, Rob Hendriks
Norway	Bodin	Björn Klöve
Germany	Eider valley, discharge site and flooded site	Astrid Knieß, Michael Trepel
Sweden	Örke (Bälinge mossar)	Kerstin Berglund, Örjan Berglund

- The Netherlands: Zegveld 3 and 13 are fields within a peat-polder which has a size of 1939 hectares. Peat thickness is 5 m. Below the peat, there is a low permeable 1.5 m peaty clay layer. The ditch water level of field 3 is about 55 cm below soil surface and of field 13 about 20 cm below soil surface. The fields are used as intensive grassland (mowing and grazing).
- Norway: The selected study site is located at the Bodin farm, Bodø, Nordland county (67° 17 N, 14° 28 E). Within a small geographical area (former mire), agricultural fields exist with different drainage and different management systems, and also a never cultivated part of the peatland (pristine mire vegetation). Agricultural sites are used as meadow, ley, or left abandoned (ley). A site was selected with a depth to mean summer water table of 77 cm in 2004. The thickness of peat layer varies between 64 - 76 cm, overlying sedimentary marine sediments (sandy loam, silt loam/ silty clay loam).
- Germany: The two study sites in Germany are located in the Eider valley peatland (approximately 400 ha). It is a minerotrophic peatland located 10 km south of Kiel. The selected peatland site (about 0.3 ha) is bordered by the river Eider, the upland mineral soils, and two ditches at both sites (figure 6.1). The upper part is mainly influenced by groundwater discharge and the lower part by floods. Peat thickness of both sites is approximately 3.5 m above a thick gyttja layer. Mean summer water tables are 22 cm below surface at the discharge site (D) and 30 cm below surface at the flooded site (F). The field has been abandoned since the mid 1990s and was used as meadow and pasture.
- Sweden: The simulated field lies within a peatland area situated north of Uppsala (approximately 1240 ha). Different fen peat types are dominating. Peat thickness is about 1 m. Ditch levels are regulated by a legal document in 1994 which states that the current land use should be maintained if possible. Mean summer water table is about 40 cm below surface. The current land use is quite moderate compared to peatland agriculture in general, with 19% annual crops (cereals), 39% intensive grassland (hey, silage) and 39% moderate grassland (pasture, moderate mowing), and 3% planted with trees.

6.3.3 Objectives of scenario studies

Different objectives for the scenario studies were formulated by the EUROPEAT partners as stated below.

- The Netherlands: The objective is to get a general view over 100 years about the way greenhouse gas emissions will develop, how large subsidence will be, and what the effect of several water management measures will be on these aspects with reference climate scenario. Central question: In which way can the model provide an easy insight as to how peatlands in the Netherlands will develop in the next 100 years under present climate, water management, and land use conditions? Special emphasis for the Dutch case will be placed on the results of subsidence, greenhouse gas emissions, and nutrient leaching.
- Norway: The objective is to test effects of different management options, business as usual, and effects of abandonment. Also, a change from annual crop to grassland will be tested, as this is a relevant scenario. The abandoned case will be tested for not active and active water level rise as a management option.

Table 6.14: Input for initial state of the scenario runs of the different countries.

Input parameter	Unit	Country ^a						
		NL	NL	G	G	G	N	SW
Site name	-	Z. 3	Z. 13	dis. a.	fl. a.	clim ^b	Bodin	i_cørke
Area	ha	1939	1939	0.175	0.1	0.175	1	7.13
Peat thickness	m	5	5	3.5	3.5	3.5	0.8	1
Land use number ^c	1 to 12	4	4	11	11	4	3	6
Mean summer water table	cm below surface	55.2	39.7	22	30	50	77	40
Standard deviation of water table	cm	15	13	6	18	6	17.7	20
Air temperature	°C	8.3	8.3	8.3	8.3	8.3	4.3	5.3
N-deposition	kg N ha ⁻¹ a ⁻¹	16	16	28	28	28	8	5
N-Fertilizer	kg N ha ⁻¹ a ⁻¹	250	250	0	0	150	150	1
Subsidence factor	-	1	1	1	1	1	3	1

^aNL = The Netherlands, G = Germany, N = Norway, SW = Sweden

^bInitial state for the climate change scenarios of Germany, based on discharge area (dis. a.)

^cCorresponding land use categories: 3 = grassland, intensive mowing; 4 = grassland, intensive mowing + pasture; 6 = grassland, moderate mowing; 11 = short time abandonment, species rich

Germany: How will the two sites develop during the next 100 years? How does water management and land use change influence site development? How does climate change and land use change on grassland influence the site development?

Sweden: The objective of the model runs is to see the effect of future land management scenarios in combination with two different climate change scenarios.

An objective with focus on selected parameters was chosen by the Netherlands. It can be assumed that the other countries want to regard all indicators, as they do not mention a focus on selected parameters. All countries want to examine the effect of land use and water management changes. Additionally Germany and Sweden want to examine the effect of climate change.

6.3.4 PMDSS input

All partners have used measurements and expert judgement or estimations to get input data. The Netherlands, Germany, and Norway additionally have used literature values. Depending on the different site conditions, there is a wide variety in input parameters (table 6.14). The site area varies between 0.1 and 1939 ha. In connection to this, it has to be considered that the Dutch partners used the size of the whole polder, where the investigated sites are fields within the polder. Peat thickness is very low in Norway (0.8 m) and high in the Netherlands (5 m). Depth to mean summer water table is lowest at the abandoned discharge site of Germany (22 cm) and highest in Norway (77 cm).

Land use types for initial state are intensive grassland in the Netherlands and Norway. For Sweden, 'moderate grassland' was chosen. For Germany, the land use and water management scenarios were started with the actual land use 'short time abandonment, species rich'. The climate change scenarios were started with 'intensive grassland' in accordance with other partner countries. The fertilizer application varies between 0 and 250 kg N ha⁻¹ a⁻¹.

Some input parameters are not in accordance with site conditions. For the Dutch sites, instead of the site specific air temperature a value of 8.3°C was used, so that the temperature factor TF is one. Norway used an area of one hectare as a reference value.

Adjustments

For German sites, no adjustments to the model were carried out. The adjustments made by the other partner countries are also included in the scenarios recalculated with the new model version.

The Dutch partners developed another hydrology module (worksheet *Mod_HydrDutch*) for the calculation of the mean summer water table and inserted adapted equations in worksheet *Mod_Adj* for subsidence rate, CO₂-emission, and N-mineralization. In the Dutch hydrology module, the mean summer water table is depending on piezometric head of the deep aquifer, ditch water levels, and the difference of precipitation (P) minus evapotranspiration (EP). The subsidence rate is depending on the mean summer water table and a temperature factor. CO₂-emission is depending on the subsidence rate. N-mineralization is depending on an N-reduction factor, C/N-ratio and CO₂-emission (WOLLESWINKEL & HENDRIKS 2006).

The Norwegian partners increased the subsidence factor in PMDSS.

The Swedish partners changed the standard fertilizer levels in *Input_Tab* to Swedish conditions (arable land: 60; intensive mowing and intensive mowing and pasture: 120; intensive pasture: 60; all other land use categories 0 kg N ha⁻¹ a⁻¹). For the redrainage scenario, for Sweden an extra equation for redrainage was introduced in *Mod_Adj*: After redrainage, the subsidence rate is higher and decreases over time to account for higher subsidence rates due to shrinkage and compression within several years after drainage. Furthermore, the Swedish partners adjusted parameters for land use category 8, but this category is not needed in the simulations.

Scenarios

To assess the effect of land use, water management, and climate change on peat soils, different scenarios were run for the case study sites of the different countries regarding typical situations in the different countries. For all scenarios, the initial state is the same as given in table 6.14, if not explicitly stated differently (one scenario of Norway, climate change scenarios of Sweden). In the following, the changes in the second model year are stated.

1. The Netherlands:

Seven scenarios for two sites additionally to business as usual were run for dry climate, different water management practises, and land use options (table 6.15). For the dry climate scenario, input data of a dry year of the site were used. Grading stands for fields with a width of 50-60 m and a surface which is in the middle about 50-60 cm higher than near the ditches (HENDRIKS, pers. comm.). Ditch water levels are set to the same distance to surface level every 10th year.

Table 6.15: Changed input data (second model year^a) of the scenarios of the Netherlands (P = precipitation, ET = Evapotranspiration, X = not performed scenario).

Scenarios	Parameter changes	
	Zegveld 3	Zegveld 13
Business as usual	(P-ET = 0; ditch water level = 55 cm below surface)	(P-ET = -35 mm; ditch water level = 20 cm below surface)
Drain level = 30		ditch water level = 30 cm below surface
	P-ET = -40 mm	P-ET = -30 mm
Dry climate	P-ET = -250 mm	X
Infiltration drains (dry climate)	tubes at 4 m distance, depth bottom 0.18 m below ditch water level P-ET = -250 mm	ditch water level = 30 cm below surface P-ET = -100 mm
Grading	P-ET = -75 mm	P-ET = -150 mm ditch water level = 30 cm below surface
Sprinkling	P-ET = 75 mm	X
Maize	land use number = 1 ditch water level = 60 cm below surface P-ET = -20 mm	X
Moderate grassland	X	land use number = 7, P-ET = -100 mm fertilizer = 50 kg ha ⁻¹ a ⁻¹

^aOriginally, the Dutch partners did the changes in first model year.

2. Germany:

- a) Land use and water management scenarios were simulated for the discharge area and the flooded area (table 6.1 on page 72):
- Business as usual
 - Rise of water level in ditches and river (rewetting)
 - Moderate pasture and regular redraining
 - Nature conservation management
 - Intensive grassland
- b) The initial state of the climate change scenarios is based on input data for the discharge site, but with intensive grassland use and at a depth to water table of 50 cm (table 6.5 on page 74). PM-DSS was run for three different water tables, once without and once with temperature increase:
- Mean summer water tables 50, 40, and 30 cm below surface
 - Linear increase of air temperature from 8.3 to 13°C

3. Norway:

For the Norwegian site, four different land use and water management scenarios are simulated:

- A. Grassland business as usual (land use number 3 to 3)
- B. From arable to grassland (land use number 1 to 3)
- C. From grassland to abandonment (land use number 3 to 12), no fertilizer
- D. From grassland to abandonment (land use number 3 to 12), raised water table to -10 cm \pm 7 cm, no fertilizer

4. Sweden:

Four land management scenarios were run for three climate change scenarios (including current climate).

- a) Land management scenarios (all land management scenarios were run for three different climate change scenarios):
- 1. Business as usual
 - 2. Rewetting (mean summer water table = 0, land use number = 12)
 - 3. Redrainage (mean summer water table = 80 cm, land use number = 1 (arable land), fertilizer = 75 kg N ha⁻¹ a⁻¹)
 - 4. Abandonment (land use number = 12¹)
- b) Climatic change scenarios:
- Control 0: Air temperature = 5.3°C
 - Scenario B2: Air temperature = 7.8°C
 - Scenario A2: Air temperature = 9.1°C

6.3.5 PMDSS results

In this chapter, the description of the results is partly following the presentation of the results by the project partners. For Germany, results of scenario studies are presented in more detail in chapter 6.1.4. For the

¹Originally, the Swedish project partners did run the abandonment scenario with change to land use number 8.

other partner countries, amoeba diagrams with the scenario results are given in Annex E. The validity of the model results is evaluated in detail in chapter 6.3.6.

The Netherlands

The Dutch partners mainly presented the results of subsidence rate, GWP₅₀₀, and greenhouse gas emissions. Three graphs were presented for every scenario: a time series graph of subsidence rate of surface, a time series graph of the GWP₅₀₀ for each greenhouse gas N₂O, CO₂, and CH₄ separately, and the amoeba diagram (figure E.1 and E.2). The calculation of the scenarios with model version 1.14 includes the Dutch hydrology module and the Dutch equations for subsidence rate, CO₂-emission, and N-mineralization.

The land use category at the initial state is 'intensive grassland' at both sites, Zegveld 03 and Zegveld 13. With the scenarios, the effect of different water management options, dry climate, and land use changes to maize and moderate grassland is examined (amoeba diagrams, figures E.1 and E.2 on pages 163 - 164).

Due to subsidence, the surface level is decreasing in all scenarios. Therefore, the influence of upward seepage is increasing. Thus, sites are getting wetter over time, despite the regular deepening of the ditch levels to the same distance to surface. Land use does not change in the water management and dry climate scenarios. Hence, in those scenarios also harvest and conservation value are not changing.

In the business as usual scenario at **Zegveld 03**, N-discharge and GWP₅₀₀ are decreasing in connection with a decreasing mean summer water table. The Dutch partners distinguish between groundwater table (the water table of the site) and ditch water table. In comparison to the 'business as usual' scenario, the subsidence rate is lower at higher drain level (30 cm below surface) and sprinkling scenarios. Dry climate and grading lead to lower groundwater tables and thus higher subsidence rates. In comparison to the dry climate scenario, infiltration drains reduce subsidence rates. The change to arable land use with maize leads to highest subsidence rates. Yet, in this scenario, land use is changing back to intensive grassland 8 years later, because the depth to groundwater table is decreasing below 50 cm. Thus, the conservation value does not change in this scenario. The decrease of harvest is not plausible. Trends of GWP₅₀₀ and N-discharge correspond to that of subsidence rate.

At the site **Zegveld 13**, the directions of development are mainly as in Zegveld 03. The subsidence rates are higher at increased drain level (30 cm below surface) and in the grading scenario. In comparison to dry climates, infiltration drains reduce subsidence rates. In the grading scenario, the groundwater table and thus subsidence rate is even higher 50 years later than at initial state. In the water management and dry climate scenarios, trends of GWP₅₀₀ and N-discharge go into the same direction as subsidence rates. Land use change to moderate grassland leads to higher subsidence rates in comparison to business as usual. This is due to higher groundwater tables with lower climatic summer water balance (P-ET). As fertilizer is decreasing, N-discharge and N₂O-emissions are decreasing. A decrease of N₂O-emission leads to an important decrease of GWP₅₀₀. This land use change leads also to a decrease in harvest.

It has to be considered that the results of development trends of N-discharge are not reliable in the Dutch scenarios (compare chapter 6.3.6).

Germany

Time series graphs as well as amoeba diagrams for all functions were given. The results are described in detail in chapter 6.1 on page 70. The initial state of the land use and water management scenarios is short time abandonment. Due to subsidence, the mean summer water table is continuously rising in the business as usual scenario. Consequently, N-discharge and GWP₅₀₀ are decreasing. Also, the conservation value is decreasing slightly. Rewetting the site leads to a decrease of N-discharge and GWP₅₀₀ and conservation value in comparison to business as usual. Land use change to 'moderate pasture', 'intensive pasture', and

'nature conservation management' increases harvest as well as the conservation value. The change to moderate pasture leads to an increased N-discharge due to less N-uptake by plants with changing vegetation type. Due to regular redraining to the same depth to mean summer water table of the site, GWP₅₀₀ remains at the same level. In the 'nature conservation management' scenario, the values of N-discharge and GWP₅₀₀ are the same as in the business as usual scenario. In the 'intensive grassland' scenario, land use is changing to moderate grassland after 17 years, as the site is getting too wet. N-discharge increases due to fertilizer application. GWP₅₀₀ is higher than at business as usual, and lower than at moderate pasture with redrainage. The trends of results apply for both discharge site (D) and flooded site (F). As the depth to mean summer water table is greater at site F than at site D, this leads to higher values of subsidence rate, N-discharge, and GWP₅₀₀ at site F than at site D (despite at the rewetting scenario (rise of water levels in ditches and river)). In the rewetting scenario, CO₂-sequestration is higher at site F than at site D, due to higher water tables. N-discharge is lower at site F. In the scenarios moderate grassland, nature conservation management, and intensive grassland, harvest is slightly higher at site F than at site D, because higher N availability leads to higher dry matter production of plants.

For the climate change scenarios, land use of initial state is set to intensive grassland use and a mean summer water table of 50 cm below surface. The decrease of the depth to water table at the reference climate leads to a faster change to less intensive land use categories. An increase of air temperature increases subsidence rates and thus accelerates land use changes in comparison to reference climate.

Norway

The Norwegian partners displayed the amoeba diagrams as results (figure E.5).

In the business as usual scenario, subsidence rate as well as CO₂-emission, GWP₅₀₀, and N-discharge are decreasing due to the decreasing depth to mean summer water table. Land use change from arable land to intensive grassland leads to a decrease in harvest, N-discharge, and GWP₅₀₀, and an increase in conservation value. Abandonment of the site leads to an important decrease in N-discharge and GWP₅₀₀, as N-fertilizer application is stopped and thus the available N and the N₂O-emission are decreasing. Also, the conservation value increases importantly with abandonment. There is only a slight difference between the abandonment scenarios: GWP₅₀₀ is lower with rewetting than without rewetting. Due to low peat thickness and high depth to water table, subsidence leads to a decrease of peat thickness lower than 30 cm after 51 or 54 years in all scenarios beside the rewetting scenario (D).

Sweden

For all scenarios, the Swedish partners presented the model results in tables for the parameters: cumulative harvest, cumulative GWP (100 years), cumulative N-discharge, cumulative subsidence, mean summer water table (mean during 100 years), land use categories at year 1, 2, 50, and 100. Amoeba diagrams were presented for the land management scenarios. The results with the new model version are presented for all scenarios in amoeba diagrams in figures E.3 and E.4 on pages 165 - 166.

In the business as usual scenario, the site is getting wetter due to subsidence. Thus, N-discharge and GWP are decreasing. Harvest is decreasing as available N is getting low (no fertilizer, decreasing N-mineralization). Conservation value remains the same as land use does not change. At the rewetting scenario, all indicators are decreasing importantly in comparison to the business as usual scenario. In the redrainage scenario, harvest, N-discharge, and GWP are increasing, conservation value is decreasing importantly. After 27 years, land use changes automatically from arable land to intensive grassland. In the abandonment scenario, the values of mean summer water table, N-discharge, and GWP₅₀₀ are the same as in the business as usual scenario. Harvest and conservation value are much lower in the abandonment scenario.

The Swedish project partners examined GWP₁₀₀ also. In difference to GWP₅₀₀, GWP₁₀₀ is highest in the rewetting scenario due to increased methane emission.

The peat thickness decreases within 100 years from 100 to 77 cm in the business as usual scenario. In the redrainage scenario, peat thickness decreases in 100 years from 100 to 47 cm.

Climate change with increasing temperature enhances land use changes, especially in the scenarios business as usual and redrainage. The warmer and wetter climate in scenario A2 compared to B2 causes a faster development in land use categories from more intensive to less intensive land use categories. In the business as usual scenario, land use changes to nature conservation management at scenario B2 in model year 82 and at scenario A2 in model year 69. In the redrainage/ 0 scenario, land use changes to intensive grassland after 36 years. In the redrainage/ B2 scenario, land use changes to intensive grassland in model year 26 and moderate grassland in model year 87. In the redrainage/ A2 scenario, land use changes to intensive grassland in model year 23, moderate grassland in model year 70.

GWP₁₀₀ is increasing with increasing air temperature, but the effect of land management is larger. The effect of temperature increase on GWP₅₀₀ is less negative in the rewetting scenario than in other scenarios.

Peat thickness decreases more in climate change scenarios in comparison to the reference climate. In the business as usual and abandonment scenarios, peat thickness is 71 cm (B2) and 68 cm (A2) in model year 100. In the redrainage scenario peat thickness is 39 cm (B2) and 35 cm (A2) in model year 100.

6.3.6 Validation

The descriptions concerning the validity of the model results are based on the statements of project partners given in the questionnaire (Annex D).

The Netherlands

The Dutch partners compared the results of the business as usual scenario for subsidence, N-discharge, and greenhouse gas emission with measurement values and values from the literature. Subsidence rate, mean summer water table, CO₂-emission, and N-mineralization are valid. This is as to be expected, because those parameters were calculated with adapted equations of the Dutch project partners. Subsidence rates are within the range of measured values on the sites. The modelled relationship between mean summer water table and subsidence rate is similar to the measured one. The simulated CO₂-emission rates are comparable to values from the literature and expert judgement.

For Zegveld 03, the N-discharge based on PMDSS calculations is about 50% lower than the estimated value based on expert judgement. For Zegveld 13, the N-discharge results are comparable with the values based on expert judgement. The relationship in PMDSS for N-discharge is not valid for the Dutch sites. N-discharge is higher at higher groundwater tables due to different hydrological conditions in combination with application of (organic) fertilizers (HENDRIKS 1993).

Calculated N₂O-emissions are 4 - 5 times smaller than values based on measurements of comparable Dutch fields (VELTHOF 1997). No CH₄-emissions correspond to literature values. As greenhouse gas emissions are valid, GWPs are valid too. The Dutch partners evaluated the scenario results in general to be plausible (except N-discharge).

It is plausible that harvest does not change if land use does not change. The decrease of harvest in the maize scenario is not plausible. It should even increase, as harvest is usually higher at intensive mowing than intensive mowing and pasture. The decrease of harvest with land use change to moderate grassland at Zegveld 13 is as is to be expected.

Germany

The validity of model results of the German study sites are described in detail in chapter 6.1.5 on page 81. In general, the results are plausible as a rough estimate of magnitude and development trend. As development of PMDSS is in a large part based on German conditions, PMDSS results are best valid for the German sites in comparison to the other partner countries.

Norway

The Norwegian partner mainly evaluated the development trend of the indicators, as visualized in the amoeba diagrams. The results were regarded as plausible with some exceptions: the increase of harvest in business as usual scenario as simulated with the old model version was not expected. With the new model version, harvest is not changing, which is plausible. As the Norwegian partner stated that the decrease of N-discharge is "perhaps surprising", the validity of this development trend is not clear. Furthermore, the Norwegian partner did not expect the change of conservation value to be so high (with change to abandonment), but also stated, to not be an expert in this field.

The very high N-discharge rates (greater than $100 \text{ kg N ha}^{-1} \text{ a}^{-1}$) are not reasonable. If the processes and conditions are similar to the German ones, development trends as given in amoeba diagrams are plausible.

Sweden

The Swedish partners stated that measured data of subsidence rates in the area have in general been greater than the ones calculated with PMDSS. The measured data include oxidation of organic matter, compaction, and shrinkage. Between 50 and 70% of the subsidence should be attributed to oxidation. KASIMIR-KLEMEDTSSON *et al.* (1997) estimated greenhouse gas emissions (CO_2 , N_2O and CH_4) from subsidence data. The resulting GWP_{100} as $\text{kg CO}_2\text{-C-equ. ha}^{-1} \text{ a}^{-1}$ from grassland (intensive) is estimated to be 3728, from cereals 6674 and row crops >19091 . They can be compared to PMDSS results (for year two) - 2683 for moderate grassland and 5613 for arable land. Measured data for rye grass in lysimeter trials in the EUROPEAT project are in accordance with the estimations of KASIMIR-KLEMEDTSSON *et al.* (1997). Thus, PMDSS results are lower, but in the same order of magnitude.

For the redrainage scenario, harvests between 3.5 and 6 t dry matter $\text{ha}^{-1} \text{ a}^{-1}$ are calculated with PMDSS. As the Swedish project partners stated that 12 and 15 t dry matter ha^{-1} (as calculated with the old model version) are almost double the normal yield level in the area (SCB 1979-1987), the modelled values might be slightly too low.

The modelled N-discharge in the redrainage scenario is very high due to a very high N-mineralization after lowering the mean summer water table. After redrainage, a N-discharge of $185 \text{ kg N ha}^{-1} \text{ a}^{-1}$ is simulated. This is too high in comparison with an investigation of a peat dominated area (70%) in Sweden with 93% arable land, where the average N-discharge between 1994 and 2001 was $31 \text{ kg N ha}^{-1} \text{ a}^{-1}$ (NÄTTERLUND 2003).

The validity of the development of the summer water table and conservation value was not checked. If processes and conditions are similar to the German ones, development trends as given in the amoeba diagrams are plausible. If subsidence rate is higher, water table should decrease faster and changes to less intensive land uses should be faster, too.

6.3.7 Feedback

In general, it was moderately clear for the users what the model was about, how to modify the parameters, and how to interpret the results (table 6.16). Furthermore, the project partners were asked to describe

6 Case studies

Table 6.16: Number of checks made by 3 project partners in the feedback table of the questionnaire.

	Quite clear what was going on	Moderately clear	Just coping	Have not got the foggiest notion
Did you fully understand what this model was about?	1	2		
Regarding the parameter modifications		2	1	
How confident do you feel about interpreting the results you got?		3		

advantages and disadvantages of PMDSS and give improvement suggestions. The feedback of the project partners is summarized below:

Advantages:

- PMDSS is an easy tool to get rough estimates of factors you want to predict and directions of changes and trends.
- The model is easy to understand and to run.
- It is accessible.
- Simple, quick, educative
- Few input parameters which are quite easy to assemble or make a qualified guess.
- User-friendly interface.
- Almost possible to see how things are calculated if you know how Excel works.
- Output tables and figures are OK.

Disadvantages:

- The values are less reliable than using models such as SWAP or ANIMO, because of the simplicity of the model.
- Not a physical approach.
- In Excel, it is not always so clear to find out what has been done.
- Not all model results are valid for the conditions in the different countries.
- Specific cases are hard to implement in the model.
- The user-friendly interface is also a danger in the "wrong" hands if you "swallow" the exact figures without criticism.

Suggestions:

- The model could be extended with more possible sites to choose from.
- It is recommended to make a clear distinction between groundwater level and drain or ditch water level in the documentation.
- Theoretical background information about the relationships applied in the model can be very helpful to understand the model and should be implemented in the documentation.
- It would be nice if you could design your own land use categories.

6.3.8 Discussion and conclusion

Discussion of scenarios

The scenarios simulated by the EUROPEAT partners all start with drained peatland sites. In the **business as usual scenarios** of the EUROPEAT sites, the depth to mean summer water table is decreasing in the next decades. The reason for this is the continuous decrease of the surface level of the sites due to subsidence. In the scenarios of Germany, Sweden, and Norway, sites are not regularly redrained. Therefore, the summer water table does not change in relation to an absolute reference level (e.g. m ASL) and the sites are getting wetter. Although the ditch water level is regularly reset to the same distance to surface in the Netherlands, the sites are getting wetter, too, because the influence of the upward seepage is increasing. In accordance with the subsidence rates, mineralization rates and thus GWP₅₀₀ are also decreasing. At the Norwegian site, the decrease of the water table is largest, due to highest depth to water table in initial state and thus highest subsidence rates.

The different scenarios of the different EUROPEAT sites present a variety of possible development directions of the ecosystem functions of peatlands in Europe.

The **Dutch scenarios** with intensive grassland use demonstrate the influence of different water management options on subsidence rate and GWP₅₀₀. Lower drainage depth and sprinkling lead to a decrease; higher drain level and grading lead to an increase of subsidence rate and GWP₅₀₀. Dry climates lead to higher subsidence rates and GWP₅₀₀. With infiltration drains, this negative effect can be reduced. The dry climate scenario demonstrates the effect of extreme droughts. This is also important to consider beside mean annual climate conditions. Also, land use change to maize (scenario of Zegveld 03) is connected with higher subsidence rates, but in this scenario the site is getting so wet that land use is changing to intensive mowing after 7 years. To avoid this land use change, either drainage depth has to be increased or redrainage has to be done more often. Consequently, costs to maintain the depth to groundwater table will rise. The amoeba diagram of the scenario with land use change to moderate grassland on Zegveld 13 (figure E.2e on page 164) would lead to the conclusion that this scenario has the most positive effect on all functions (beside the production function). It is not visible in the amoeba diagram that the subsidence rate is higher in comparison to business as usual. Reduction of GWP₅₀₀ is high, mainly due to decreasing N₂O-emission. As N-discharge description in the model is not valid for the Dutch sites, it might increase in difference to the model results. Thus, higher water tables suggest good results for N-discharge in the amoeba diagram, but it might be the other way around in the field. The moderate grassland scenario is the only scenario where the conservation value is increasing. If the land use remains at intensive grassland, harvest and conservation value will not change.

Peat thickness will decrease in all countries if the sites remain drained. The threat of the disappearance of the peat soil is especially high at thin peat layers and low water tables, as the Norwegian scenarios exemplify. In the Swedish scenarios, the thin peat soil remains for more than 100 years. Yet, especially with redrainage and more intensive land use, the peat layer is also dangerously reduced. At the Dutch and German sites with peat layers of 5 and 3.5 m respectively, reduction of the peat layer is a more subordinated problem, regarding the next 100 years. In all cases, rewetting the site is the only way to stop subsidence. Other activities reduce the subsidence, such as rise of water table and land use change to less intensive land use types. Especially at the Norwegian and Swedish sites, options have to be checked to rescue the peatlands. If in Norway intensive grassland shall be kept, this is also possible with higher summer water tables. Land use change to less intensive use or rewetting would be more valuable.

Change from arable land to intensive grassland at the **Norwegian site** has a positive effect on all functions

beside production function. The results of the Norwegian scenarios with change to abandonment, both with and without rewetting, suggest a more extreme improvement of peatland functions. As N-discharge and N₂O-emission will be lower in initial state, changes will be not that high.

The **Swedish scenario**, change from moderate grassland to abandonment with rewetting, has the most positive effect on the development of N-discharge and GWP₅₀₀ in comparison to business as usual. On the other hand, conservation value and harvest are decreasing. An abandonment of the site without rewetting is not improving any function. The values of subsidence, N-discharge, and GWP₅₀₀ are like in the business as usual scenario, but harvest and conservation value are decreasing. Redraining the site for the use of arable land is even worse for most functions, only the increase in harvest is positive. N-discharge and GWP₅₀₀ are increasing, conservation value is decreasing. If the GWP₁₀₀ is regarded, the scenarios might be evaluated differently, as GWP₁₀₀ is higher at rewetting in comparison with business as usual due to increased methane emissions. Thus, the Swedish partners stated that to abandon the site is a better alternative than rewetting if Global Warming Potential is calculated for a time horizon of 100 years, but the opposite with a time horizon of 500 years.

A detailed discussion of the scenario results for **Germany** is given in chapter 6.1.6 on page 81. In difference to other partner countries, sites are abandoned in initial state. A change to nature conservation management seems to be a good compromise for the development of all peatland functions. N-discharge and GWP₅₀₀ do not change in comparison with business as usual scenario, but harvest and conservation value are increasing. Change to moderate grassland or intensive grassland leads to higher GWP₅₀₀ and N-discharge. The change to more intensive land use demonstrates, that the land use will change if the site will not be redrained regularly.

Climate change leads to enhancement of subsidence as the German and Swedish climate change scenarios show. This results in faster changes to less intensive land uses as well as to faster wetting of the site and faster decreases in GWP₅₀₀ and N-discharge rates.

The scenario results exemplify that effects of land use and water management and global climate change on the development of ecosystem functions on peat soils vary depending on the initial situation of the specific sites.

Applicability of PMDSS to the EUROPEAT sites

From the evaluation of the validity of model results for the different sites of the European partner countries (chapter 6.3.6) it can be concluded that PMDSS is applicable with some limitations. PMDSS is best valid for the peatland sites in northern Germany. The applications to the European sites show that PMDSS seems to be a good concept to extend the model for more different countries and situations.

In general, the results of N-discharge are too high if mineralization rate and/ or fertilizer application are high. In those cases it can be assumed that denitrification is higher than modelled. Thus, some parameter changes are necessary in the nitrogen module. To account for deep summer water tables and high fertilization rates, a maximum value for N-discharge should be introduced in PMDSS and the distribution factor *fn* should be changed (table 4.8 on page 40). Different relationships between summer water table and N-discharge have to be introduced, depending on different landscape and land use characteristics in Europe. For instance, at the Dutch site, N-discharge is increasing with rising water tables, which is the other way round than implemented in PMDSS. For Norway and Sweden, more investigations about the factors effecting N-discharge are necessary.

The adjustment possibilities in PMDSS have been used to get more reasonable results for the specific sites. A model concept with adjustment possibilities makes the model more flexible for transmission to different situations in Europe and for further extension. Adjustments of PMDSS by the user are only possible for the

parameters in which the user is an expert.

The development of an own hydrology module by the Dutch partners suggests an extension to the existing hydrology module of PMDSS. The existing hydrology module could be extended in a way that includes the change of bottom flux due to subsidence of surface. The Dutch hydrology module also suggests to include vegetation depending evapotranspiration rates in PMDSS.

To make PMDSS directly applicable to redrainage scenarios without adjustments (compare adjustments of the Swedish partners for the redrainage scenario), different subsidence equations for different degradation degrees of peat soils are necessary. Also, the proportion of subsidence connected to mineralization depends on soil properties. On arable land, subsidence rates as well as mineralization rates are depending on crop type. This could be introduced into the model.

The Swedish partners suggested to include a possibility for the user to create own land use types. As vegetation types are connected to the land use categories in PMDSS, this is only partly possible to implement in PMDSS.

In the new model version, the results of harvest are in a realistic order of magnitude, but the validity of the results were not fully evaluated. The validity of the results of the conservation value of partner countries were not tested either. To evaluate the applicability of PMDSS to the different European countries, further investigations are necessary. The validity of the model results is site specific as well as parameter specific. Further cooperation with experts of the different countries for the different peatland functions would be valuable.

Userfriendliness and understandability of PMDSS

One aim was to make PMDSS easily understandable, so a wide range of people with different knowledge backgrounds should be able to use it (chapter 4.1). With the application of PMDSS by the project partners, the usability and understandability of PMDSS was tested by a selected group of stakeholders. As researchers, the project partners are experts in abiotic processes on peatlands. They got a one-day introductory course on how to use a previous version of PMDSS and could always ask for help. The general outcome of the questionnaire is that the userfriendliness and understandability of PMDSS is evaluated as moderate by the project partners. This is confirmed by the analysis of the results of the model applications.

From feedback and suggestions by the project partners and the analysis of the answers to the questionnaires, improvement possibilities will be concluded in the following.

Although a rough estimate of input data is sufficient, exact values are needed for the input. This is animating intensive data analysis to get input data. This might be not in accordance with the aim that input data should be easily collectable within a few days (chapter 4.1). For instance, the Dutch partners performed a very intensive statistical analysis of input data to get mean long-term summer water table of the site and ditches and the climatic water balance of the summer. Despite that, the results have to be interpreted as rough estimates. Depending on the background knowledge and available data, the values of the different input parameters might get unequally precise. As adapted equations were used for the Dutch sites, in this case the output for the corresponding parameters may be interpreted as exact. Results derived from this output are again to be interpreted as rough estimates.

Some input mistakes made by the users emphasize that more help with input is needed. (1) Originally, the Dutch partners set the land use in the maize scenario to arable land in the first year only. In the second model year, land use was left at intensive grassland in the input. This was obviously not recognized by them. (2) The Swedish partners made some adjustments which were not in accordance to the model concept. The parameters for land use category 8 were adjusted in worksheet *Input_Tab*: next land use when high ground water level = 10, harvested portion = 0, no pasture. This is in contrast to the associated vegetation type,

which then does not fit any more to the land use. The next land use number 10 does not work for the vegetation module; this is only allowed as a starting point. (3) While copying the amoeba diagrams from PMDSS into the document with the results, two partners (The Netherlands, Sweden) overlooked the carrier function. Thus, land use changes have not been noticed.

The results were interpreted and it was explained how they were achieved. Some explanations of indicator results are derived from further parameters (worksheet *Res_TimeSeries*). For others, detailed knowledge about model equations as well as insight into module worksheets is necessary. This cannot be expected from the normal model user. More, this is underlined by the suggestion of one project partner to include more background knowledge about the relationships applied in the model.

Some conclusions can be drawn from the analysis described in the last paragraphs. Further improvement to help the user to make the correct inputs and to interpret the results is worthwhile. This also includes a better traceability of how the results are calculated. Text output may be extended. The classification of the indicators (into categories such as high, middle, low) could be used for the input and in the results graphs as well. Additionally, further text with interpretation of the results could be introduced. With some rules, this knowledge could be made accessible for the user. To prevent input mistakes, more restrictions for the input are needed. The user should not be able to make implausible input or model adjustments.

As it is with every model, the user has to know what it is for and how to use it. PMDSS is easy to use - this includes the danger of misusing it.

7 Discussion and conclusion

Within this thesis, the Peatland Management Decision Support System (PMDSS) was developed which is a semi-quantitative and one-dimensional model for the prediction of long-term changes (100 years) of peatland functions at the site scale. PMDSS is adapted for application to minerotrophic peatland sites in Europe used for agriculture, forestry, and nature conservation as well as to abandoned sites. With annual time steps, it calculates the development of different indicators relevant for peatland functioning. The applicability of the model was tested for three case studies (see chapter 6).

In the following, methodological and application issues of PMDSS will be discussed. Possible uses and contributions of the model for the management of peatlands are concluded. The indicators used in PMDSS are set into the context of existing international indicator sets. PMDSS is compared with existing decision support systems and models. Strengths and limitations of PMDSS with regard to its userfriendliness and understandability are examined. The application area will be concluded from the model development and the evaluation of case studies. The use of PMDSS within the context of sustainable peatland management is examined and possible development trends of peatlands in Europe are discussed. Finally, an outlook for further application and improvement of PMDSS concludes this chapter.

7.1 Methodology

Indicators

The model is based on specific indicators with the aim of describing the long-term changes of peatland functions at the site scale. For the peatland functions production for agriculture/ forestry, carrier function, regulation of catchment hydrology, regulation of catchment hydrochemistry, regulation of global climate and existence of plants, animals and ecosystems, the following indicators were selected (see chapter 4.2):

- Harvest of plant products
- Land use category
- Mean summer water table
- Nitrogen discharge
- Global Warming Potential
- Conservation value of plants

The indicators of PMDSS are related to indicator sets used at national and international levels: Millennium Ecosystem Assessment (MA), the Organisation for Economic Co-operation and Development (OECD) and the European Environmental Agency (EEA). The international indicators sets are used for the assessment of consequences of ecosystem change for human well-being on local, regional, and global scale (MA 2005a, 2005b), for reporting the state of environment and progress towards sustainable development on the national scale (OECD 2003, 2007), and for describing trends in and prospects for the environment on the national scale (EEA 2005).

While dealing with indicators, the regarded scale is important (detailed discussion see MA 2003). Three scaling categories can be distinguished: scale-independent, scale-dependent with known scaling rules, and non-scalable (MA 2003). The indicators of PMDSS are scalable and thus comparable with national and international indicator sets. Nevertheless, it has to be kept in mind that the indicators for PMDSS were chosen for the site scale. Another important scale regarding peatland functioning is the catchment scale which is not regarded in PMDSS. Indicators such as 'flood storage' and 'nutrient retention' are relevant in order to reflect problems of peatland use relevant for this scale (see chapter 2).

The indicator 'harvest of plant products' is comparable to food production (yield) used by MA (2005a). The indicator 'land use category' can be set in relation to change in land use (OECD 2003) or change in area and use of grasslands (EEA 2005). As the indicator 'mean summer water table' is an important variable concerning the water balance of peatlands (see chapter 4.3.7), it can be connected with groundwater recharge/discharge, both of which are used for the assessment of wetlands (MA 2005b). The indicator 'nitrogen discharge' is comparable with nutrient surplus (EEA 2005) and removal of excess nutrients (MA 2005b). The indicator Global Warming Potential is important with regard to the Kyoto protocol of the United Nations Framework Convention on Climate Change (UNFCCC). In difference to PMDSS (see chapter 4.3.6), the GWPs of the 100 years horizon with the factors of IPCC (1996) are summed up for six greenhouse gases: carbon dioxide, methane, nitrous oxide, and three groups of fluorinated gases. This parameter is included in the parameter sets of EEA (2005) and OECD (2007). Also in the MA (2005b), the sources of and sinks for greenhouse gases are used as indicators. The indicator 'conservation value of plants' is based on red lists, which is in accordance to indicators used in other sets: threatened species (MA 2005a), threatened and protected species (EEA 2005).

The comparison of the indicators of the present study with indicator sets used at national and international level emphasizes their relevance within this context. Thus, PMDSS might contribute with the evaluation of long-term changes of peatland functions to assess consequences of ecosystem change for human well-being, to report the state of environment and progress towards sustainable development and to describe trends in and prospects for the environment.

Models

In order to calculate the development of the selected indicators and additional parameters for a time span of 100 years (vegetation 50 years), PMDSS is divided into seven modules: subsidence, sand use, carbon, nitrogen, Global Warming Potential, vegetation, and hydrology. In PMDSS, the interactions between the modules are represented. Especially drained agricultural used peatlands are continuously changing their status due to subsidence and consequent vegetation adaptation. Changes in the forcing functions land use and water management may cause abrupt system changes. Different calculation methods are integrated in PMDSS. The system behaviour is described with regression equations (e.g. subsidence rate, CO₂-emission, CH₄-emission, N-mineralization), simple rules (e.g. peat growth, N-discharge, N₂O-emission, mean summer water table, land use change), a Markov chain model based on plant groups (vegetation module), and analytical solutions of a quasi stationary concept (hydrology module).

PMDSS differs from other existing decision support systems for peatlands and wetlands due to the integration of all peatland functions in one model in combination with the simulation of long-term changes (see table 7.1). Several model characteristics of the Wetland Evaluation Decision Support System (WEDSS) (JANSSEN *et al.* 2005, MALTBY 2005, table 7.1) are comparable to PMDSS. WEDSS covers a comprehensive set of wetland functions. The assessment of the performance of the wetland functions in WEDSS is based on small units which are homogeneous with respect to functioning (comparable to the site scale used

for PMDSS). To obtain a final outcome of the performance of the functions for the whole wetland, results of each unit are summed up weighted by the unit areas. In difference to PMDSS, WEDSS provides a GIS based tool for the assessment procedure. An important advantage of PMDSS in comparison to WEDSS is the simulation of long-term changes of the peatland functions with semi-quantitative modelling methods. In WEDSS, only a single state is assessed.

An advantage of the other DSSs listed in table 7.1 in difference to PMDSS is the reference to the catchment, landscape, or ecosystem scale. On the other hand, most DSSs do not model long-term system changes of system components, including the interactions between those. Furthermore, most DSSs are restricted to

Table 7.1: Comparison of PMDSS with several decision support systems which assess the effect of land use/ water management options on functions of peatlands/ wetlands.

Model	Model objectives	Calculation methods	Target parameters/ information	Spatial scale	Time scale	Application area
PMDSS (present study)	Prediction of trends in long-term changes of peatland functions	Semi-quantitative (regression equations, rules, markov chain model, analytical solution)	Harvest of plant products, Land use category, Mean summer water table, Nitrogen discharge, Global Warming Potential, Conservation value of plants	Site	100 years	Minerotrophic peatlands in Europe
WEDSS (JANSSEN <i>et al.</i> 2005, MALTBY 2005)	Functional assessment of wetlands	Set of tools (multi-criteria analysis, spatial database, knowledge base, assessment map)	Parameters of water quality, climate change, biodiversity and biomass, water quality, heritage, local economy	Catchment	Single state	Wetlands in Europe
WETTRANS (TREPPEL & KLUGE 2004)	Assessment of nitrogen retention ability	Matrix model with quasi-stationary mass balance approach	Nitrogen retention	Catchment	Single state	Riperian peatlands in the state Schleswig-Holstein, Germany
PRisiko (TREPPEL 2004a)	Risk assessment of phosphorus leaching from rewetted peat soils	Equations	Phosphorus decomposition	Site in relation to river	25 years	Minerotrophic peatlands in the state Schleswig-Holstein, Germany
DSS-WAMOS ^a	Optimal proposal for restoration measures in forest mires	Decision trees in a modular concept, matrices	Target species/ biotope	Peatland	Single state	Mires in the forest in Germany
DSS for raised bogs ^b	Check for pitfalls in the restoration process and provision of guidelines to avoid them	Decision tree	Target species and species groups	Landscape	Single state	Raised bogs in Europe
DSS of ASSHOFF (1996)	Guidance for management of wet meadows	Rules, objects, fuzzy-sets	Vegetation succession	Ecosystem	Decades	Wet meadows in northern Germany
Elbe-DSS (KOFALK <i>et al.</i> 2004)	Provision of information for administrative tasks to implement the Water Framework Directive	Set of tools (user interface, tool-kit, simulation kernel and models, GIS/database)	Water quality/ reducing pollutant loads, flood control/flooding risks, ecological state of floodplains, climate change, agricultural policy, demographic developments	Catchment	Single state	River Elbe catchment in Germany

^a<http://www.dss-wamos.de/>

^b<http://www.barger.science.ru.nl/life/decision-tree/>

one or only few target parameters. Several models regard only one development direction: rewetting or restoration of peatlands. The Elbe-DSS is differing from the other models listed in table 7.1, as it was developed for a special catchment and for the support of the implementation of the European Water Framework Directive (WFD) (KOFALK *et al.* 2004). The wetland functions are covered comprehensively by the target parameters and information. As the Elbe-DSS is exclusively optimized for modelling the River Elbe catchment, it is used for more detailed assessments of the effect of management options and for implementing management measures in the context of the WFD.

Beside decision support systems, further model types are available, which can be used to simulate the development of individual or a small set of peatland functions. Process-based water and nutrient models (e.g. SWAP/ ANIMO (VAN DAM 2000, RENAUD *et al.* 2005), SWAT (ARNOLD *et al.* 1998), WASMOD/ STOMOD (REICHE 1996)) and the water balance model for riparian wetlands Feuwa (DALL'O' *et al.* 2001) have a high demand on input data and have to be partially adapted to peatland conditions, such as the integration of a subsidence process. Many vegetation models have been developed to predict the occurrence of plant species or vegetation types in relation to hydrological or hydrogeochemical habitat conditions (VENTERINK & WASSEN 1997).

So far, existing model approaches and research activities focus on selected aspects of peatland investigations and management at different temporal and spatial scales. With PMDSS, a gap was filled among the variety of existing DSSs and models which are focused on specific aspects of peatland investigations and management at different temporal and spatial scales. In contrast, often simple estimations are made by practitioners in the field. Long-term predictions of the development of a peatland site are possible with PMDSS regarding a comprehensive set of peatland functions and the interactions between the system components. This is thought to be a valuable approach for initial decision making process concerning peatland management.

Userfriendliness

A user-friendly decision support tool must be easy to use by anyone familiar with computers and little background knowledge of the subject (UBBELS & VERHALLEN 2000). The tool should be easy to learn and to remember and the information should be provided in a meaningful form. GOOSEN *et al.* (2007) list a possible pitfall for DSS development concerning userfriendliness, which is that "users cannot interact with software that is too complicated or lacks transparency" (p. 189).

The userfriendliness and understandability of PMDSS was evaluated by EUROPEAT project partners (chapter 6.3.7) and is discussed in detail in chapter 6.3.8. Although PMDSS was tested with scientists of the EUROPEAT project (which represent only a certain group of possible stakeholders), some general conclusions about the userfriendliness of PMDSS are possible. The general feedback of the project partners was that the userfriendliness and understandability of PMDSS is adequate. The tool is easy to use, but in "wrong" hands there is the danger of misusing PMDSS and misinterpreting the results. On the one hand, the input is simple and the results are represented in easily understandable graphs. On the other hand, input mistakes made by the users emphasize that more help with the input is needed. Another limit of the model is that - although a rough estimate of input data is sufficient - exact values are needed for the input. This animates the user to make intensive data analysis to get input data. Because exact values are also given in the output, the interpretation of the results as a rough estimate of the development trend is not properly supported by the model output. Furthermore, the project partners stated that there is a need for more background knowledge about the relationships applied in the model.

It can be concluded that PMDSS is easy to use, but some background knowledge of the subject as well as

some insight into the functioning of the model is needed. Thus, it is recommended that PMDSS is applied by a model expert together with the relevant decision-makers and stakeholders.

7.2 Application of PMDSS

Area of application

Application areas of PMDSS are minerotrophic peatland sites in Western, Central, and Northern Europe which are used for agriculture, forestry, nature conservation, and abandoned land. The model development was focused on countries with regard to EUROPEAT project partners. As the vegetation module includes only the red lists of EUROPEAT partner countries, the present model version is restricted to Germany, Great Britain, the Netherlands, Norway, Poland, and Sweden. Yet, PMDSS can be easily extended with red lists of threatened plant species of other countries. Furthermore, PMDSS was developed for peat soils which have been drained already for at least 7 years, where subsidence occurs mainly due to mineralization, while subsidence due to irreversible shrinkage and compression is negligible (see chapter 4.3.1).

The applicability of PMDSS was tested for three case studies (chapter 6). The evaluation of those case studies shows that overall, PMDSS gives reasonable results with certain limitations (described in detail in chapters 6.1.5, 6.2.5, 6.3.6). With an imprecise data basis and roughly estimated input data, reasonable results can be achieved with PMDSS (e.g. case study Mötjempolder, chapter 6.2). The model results point out the potential order of magnitude and the trend of peatland development via the described indicators. The model is best valid for peatland sites in northern Germany at high summer water tables (see case studies Eider Valley and Mötjempolder, chapter 6.1 and 6.2). This accounts for the circumstance that all modules are mainly based on conditions of northern Germany. Furthermore, at sites with high N-availability (connected with low summer water tables and high fertilizer rates), PMDSS calculates the N-discharge rates too high (see figure 6.12 of case studies Mötjempolder and sites of the Netherlands, Norway, and Sweden in chapter 6.3.6). PMDSS is designed for hydrological conditions, where upward/ downward groundwater seepage and fast surface runoff does not occur (compare scenarios of the Netherlands in chapter 6.3.6). Although groundwater seepage is included in the hydrology module, its changing influence over time in connection with the subsidence of surface is not included. Beyond this fact, the hydrology module was not applied in the case studies; thus, its plausibility still needs to be tested. Moreover, the plausibility of the results of the vegetation module has not been evaluated for the partner countries with the exception Germany.

The concept of PMDSS seems to be well suited for adapting the model to different regional and site specific conditions (discussed in detail in chapter 6.3.8). The adjustment possibilities in PMDSS make the model flexible for transmittance to different situations in Europe. Project partners used the adjustment possibilities to adapt the model to own conditions, such as the inclusion of another hydrology module, adapted equations for subsidence rate, CO₂-emission, N-mineralization, the increase of the subsidence factor, or the change of the standard fertilizer levels (see chapter 6.3.4). Further investigations and incorporation of expert knowledge are necessary to evaluate and improve the applicability of PMDSS to more European peatland sites and all peatland functions.

PMDSS in the context of sustainable peatland management

During the last centuries, large mire areas were claimed for the use as agricultural land. The priority in peatland use on the production function leads to degradation and loss of peat soils. With the increasing

7 Discussion and conclusion

awareness of the resulting problems, other functions of peatland ecosystems (regulation, informational, carrier functions) are receiving more attention.

Many stakeholders such as land owners, water boards, environmental agencies, visitors, hunters, and researchers have interests in peatlands. They all have differing rights and interests in using a peatland site. Every stakeholder has his own priorities concerning the peatland functions and varying properties and rights for the peatland sites. The decisions of the land owners about peatland management are influenced by economic conditions, agricultural, and environmental policies.

The main driver for wise and sustainable use of peatlands at an international level are the Guidelines for Global Action on Peatlands of the Ramsar Convention on Wetlands (RAMSAR CONVENTION SECRETARIAT 2004). Based on the definitions of wise use of RAMSAR CONVENTION SECRETARIAT (2007) (chapter 3.2) and sustainable development (WCED 1987, see Glossary), the following definition of sustainable use of peatlands is given:

Sustainable use of peatlands means to apply land use and water management options at peatland sites, considering long-term aspects of ecological, economical and social functions of the peatland ecosystem to meet the needs of the present without compromising the ability of future generations to meet their own needs.

As drained peatlands are subject to mineralization and subsidence, sustainable use of peatlands is connected to conservation and restoration to preserve peatland ecosystems for future generations. For the development of sustainable management concepts of peatland sites, taking into consideration the development and long-term changes of all peatland functions is essential. Due to the complexity of peatland ecosystems, tools are needed to predict peatland development.

PMDSS is representing the complex interactions in a peatland ecosystem in a simplified model. A decision-maker can identify long-term effects of management options to the peatland functions. This may help to define realistic management targets. Thus, more aimed investigations and resources are supported to implement management measures. The effect of different management scenarios can be compared for one site. To apply PMDSS to a whole peatland (which cannot be described by a single site), several subareas can be distinguished for which the model is applied separately (e.g. case study Mötjenspolder, chapter 6.2). Furthermore, PMDSS can be used as a tool to compare the differences between management strategies and their potential effects in different European countries (e.g. case study EUROPEAT sites, chapter 6.3).

PMDSS is usable in decision making about future land use and water management options for peatland sites. It is able to support the decision maker to regard all peatland functions and to integrate the main stakeholders in the decision making process. Furthermore, this tool may help to document the assumptions for decision-making, which increases the transparency of the decision basis. For an examination of realistic management targets, the following questions may be answered with PMDSS (compare case studies, chapter 6):

- How will the peatland functions of a site potentially develop during the next 100 years?
- What are the possible effects of different land use and water management options on the development of the peatland functions?
- What are the possible effects of an increase in air temperature due to climate change on the development of the peatland functions?

Plausibility of scenario results achievable with PMDSS

The results achieved with PMDSS give an orientation for a development trend of the sites and the order of magnitude of the indicator values. Typical trends and issues for the development of peatland sites in relation to management scenarios are summarized and discussed in the following paragraphs. In each paragraph, first the issue is described and the results of PMDSS in terms of peatland development are outlined (referring to the case studies in chapter 6). Secondly, the plausibility of the results is discussed against the background of the state of knowledge.

The description and discussion of the PMDSS simulation results are limited to the application area as was stated in the according paragraph on page 117. The discussion of the vegetation development and the indicator results for the conservation value of plants is restricted to Germany, unless simulation results of peatland sites of other countries in Europe show the same development trend.

Intensification of land use

Intensification of peatland use is usually connected with an increase in drainage depth and fertilizer application. In PMDSS, intensification is referring to land use changes within the sequence nature conservation management - moderate grassland - intensive grassland - arable land. The model results show an increase in the GWPs of all three time horizons, rising N-discharge rates, and a decrease of the conservation value (e.g. scenarios E of Eider Valley sites in chapter 6.1, scenario redrainage of Sweden in chapter 6.3). In general, the harvest of plant products is also increasing with land use intensification, but occasionally the trend is reversed due to differences in the amount of harvest depending on the type of land use, such as mowing or grazing, and on the crop type (compare table 4.7).

The decreasing conservation value in conjunction with increasing land use intensity is in agreement with a marked decline in species richness and the number of endangered species with retrogressive succession changes from small sedge reeds via wet meadows to wet pastures (SCHRAUTZER *et al.* 2007, KORSSELMANN & VERHOEVEN 1995, GROOTJANS *et al.* 1986). GWPs are generally higher at more intensive land use types (BYRNE *et al.* 2004). As nitrogen availability is usually higher at more intensive land use types, N-discharge is increasing with land use intensification despite of the increasing N-uptake by plants (HENDRIKS 1993). Thus, the modelled development trends of the GWPs and N-discharge seem to be plausible. The results for the harvest of plant products are in accordance with literature values (table 4.6).

Extensification of land use

At extensification of peatland use within the sequence arable land - intensive grassland - moderate grassland - nature conservation management, the model results show a decrease of the GWPs and N-discharge rates and an increase in conservation value (e.g. subarea 6 of Mötjempolder in chapter 6.2, scenarios moderate grassland of the Netherlands and B of Norway in chapter 6.3). The model results are reverse to the ones for land use intensification.

Long-term experiments showed that mowing once or twice a year with low fertilizer input or without fertilization (corresponding to moderate grassland and nature conservation management in PMDSS) enhances the species richness and increases the number and coverage of target species (species of wet meadows and small sedge reeds) in degenerated peatlands (SCHRAUTZER *et al.* 2007). Extensive broadscale grazing (corresponding to nature conservation management in PMDSS) seems to be an option to increase biodiversity, too. However, no field experiment is known where the full range of characteristic and threatened species of small sedge reeds could be reached with regular mowing (SCHRAUTZER *et al.* 2007). The development of target species is often limited by low density or absence of relevant seeds in the peat soil (JENSEN 1998). Furthermore, problems with re-establishing target species are due to difficulties in restoring hydrological

systems of fen areas (GROOTJANS *et al.* 1996, VAN DIGGELEN *et al.* 1994) and the almost irreversible change of physical soil parameters (ILNICKI & ZEITZ 2003). Moreover, dispersal vectors (e.g. flooding (hydrochory) or propagation by livestock (epi-, endozoochory)) are often missing in the cultural landscapes of Central Europe (BAKKER *et al.* 1996). Consequently, in many cases the restoration of wet meadows and small sedge reeds can only be efficiently enhanced with top soil removal and sowing of target species or seed transfer with plant material (PRACH 2007, RASRAN *et al.* 2007). The model results for GWPs, N-discharge, and harvest of plant products are plausible due to the same reasons as stated for intensification in the last paragraph.

Regular redrainage

If it is desired to maintain a land use category in PMDSS (beside 'abandonment' or 'none'), the sites have to be redrained regularly. Otherwise the site is getting too wet and land use is switching to a less intensive one (e.g. scenarios C and E of Eider Valley sites in chapter 6.1, scenario maize of the Netherlands in chapter 6.3). The required redrainage frequency is depending on the subsidence rate and thus on the mean summer water table and land use intensity.

Regular redrainage or land use changes due to the fact that peatlands are getting wetter due to subsidence are common on peat soils (TREPPEL 2003, SCHOUWENAARS 2002, HELLEGERS 2001, SCHRAUTZER & WIEBE 1993).

Decrease in peat thickness

Due to subsidence at all drained peatland sites, a decrease in peat thickness is simulated. Usually, the farmer is not aware of this slow process leading to a decline in peatlands in Europe. Peatlands with thin peat soils (< 1 m) are especially endangered to disappear. Within a few decades, peat soil is gone if the site is left drained (e.g. scenarios A, B, C of Norway, chapter 6.3). A rise of the water table will slow down this process and rewetting will stop it or even has the potential of peat growth.

Those results are in agreement with the present state of knowledge (see chapter 4.3.1.1).

Abandonment

With PMDSS it is simulated that the abandonment of sites with moderate grassland use and nature conservation management sites leads to a decrease in conservation value. The same applies for leaving short-time abandoned sites further abandoned. Long-term abandonment is connected with a development of trees after 20-40 years (e.g. scenarios A of Eider Valley sites in chapter 6.1, scenario abandonment of Sweden in chapter 6.3). Moreover, abandonment leads to a decrease in N-discharge and GWP₅₀₀ due to an increasing summer water table. GWP₂₀ and GWP₁₀₀ are initially also decreasing, but increasing at higher water tables. The starting methane emission at a depth to mean summer water table of 15 cm is strongly influencing the Global Warming Potential values.

According to a decrease in the conservation value, secondary progressive succession on peatland sites due to abandonment usually causes a decrease in plant biodiversity (WOŁEJKO 2002, SCHRAUTZER & JENSEN 1999, FOJT & HARDING 1995, ROSENTHAL 1992). Small sedge reeds and wet meadows (associated with nature conservation management and moderate grassland in PMDSS) contain most endangered species, concerning the vegetation types used in PMDSS (HOLSTEN 2006). Therefore the conservation values at the initial state in PMDSS are high and medium for the corresponding land use types. Nevertheless, all alder carrs are classified to be worthwhile for conservation purposes and many of them are endangered (DUENE E.V. 2005). The prediction of the point of time at which the development of alder carrs is starting after abandonment is difficult and depends on the previous land use. Alder trees can occur 5-10 years after grazing, but wet meadows may stay stable over 50 years (SCHRAUTZER *et al.* 2007). This cannot be estimated with

PMDSS. The change of the mean summer water table is influenced by several processes working in opposite directions. Subsidence and a continuous closure of ditches by plants causes an increasing water table, which is in accordance with the PMDSS results. The development of trees might result in a decrease of the mean summer water table, due to higher evapotranspiration rates (PRICE *et al.* 2003). The latter would result in higher N-discharge rates and GWP₅₀₀ than simulated. The increase of GWP₂₀ and GWP₁₀₀ would start later or would not take place.

Moderate land use after short time abandonment

At land use change to nature conservation management after short time abandonment, PMDSS simulates an increase in conservation value (e.g. scenarios D of Eider Valley sites in chapter 6.1). Due to an increasing mean summer water table, N-discharge and GWP₅₀₀ are decreasing. At low water tables, GWP₂₀ and GWP₁₀₀ are also decreasing, but increasing at higher summer water tables due to methane emission.

As described in detail for extensification of land use on page 119, nature conservation management and moderate grassland result in increasing species richness and the development of target species. After abandonment, the potential for reestablishment of target species might be higher, due to the conservation of long-term persistent seed banks (SCHRAUTZER *et al.* 2007, SCHWARTZE 2003, HALD & VINTHER 2000). The simulated development trends of N-discharge and GWPs are comparable to the abandonment scenarios (see last paragraph) and are plausible due to the increasing mean summer water table.

Rewetting

In PMDSS, a decrease of conservation value is simulated after rewetting of abandoned sites or moderate grassland (e.g. scenarios B of Eider Valley sites in chapter 6.1, subarea 2 of Mötjerpolder in chapter 6.2, scenario rewetting of Sweden in chapter 6.3). This result is connected with a simulated development of reed. N-discharge and GWP₅₀₀ are decreasing. GWP₂₀ and GWP₁₀₀ might increase due to the high methane emission rates. At rewetting of forest, the conservation value is changing insignificantly (subarea 3 of Mötjerpolder in chapter 6.2). Furthermore, rewetting leads to a peat forming process.

Limits of the implementation and success of rewetting are not considered in PMDSS. The possibility and success of rewetting a peatland site mainly depends on the hydrological system and type of water (GROOTJANS *et al.* 2002, KRATZ & PFADENHAUER 2001). Furthermore, the costs for rewetting are usually high and the hydrological influence is often going beyond the rewetted peatland area. The low conservation value associated with reed in PMDSS reflects how the majority of the reed plant groups in the state Schleswig-Holstein, northern Germany, were classified: four of six reed plant groups occurring on peat soils are not endangered and two were classified as endangered (DIERSSEN *et al.* 1988). As reed includes peat-forming species, the starting peat forming process is plausible after rewetting. Often rewetting of peatlands leads to an increase in GWP₁₀₀ (AUGUSTIN & JOOSTEN 2007). This is explained with increased CH₄-emission, remaining high CO₂-emission, and a drastic increase in N₂O-emission due to water level fluctuations. The different development trends of GWP₂₀, GWP₁₀₀ and GWP₅₀₀ in simulations with PMDSS may underline the uncertainty in the long-term effect of rewetting on greenhouse gas emission rates. As AUGUSTIN & JOOSTEN (2007) suggest in their scenarios, the Global Warming Potential might decrease after flooding in the long run. The simulated decrease of N-discharge after rewetting can be confirmed by measurements on peatland sites (SCHRAUTZER 2004).

Climate change

Climate change will influence the development of peatland functions. For scenarios with increasing air temperatures, PMDSS simulates enhanced subsidence and mineralization rates. In comparison to the conditions at present climate, faster subsidence leads to a faster wetting and this in turn to a greater decrease in

GWP₅₀₀, N-discharge, and in depth to water table (e.g. case study Eider Valley, chapter 6.1 and case study EUROPEAT sites, chapter 6.3).

The higher subsidence rates with higher air temperatures are obvious and were therefore included in PMDSS (chapter 4.3.1.2), but this includes the assumption of stable evapotranspiration rates. If change in precipitation and evapotranspiration will be accounted for in PMDSS, the results for the climate change scenarios might be different.

7.3 Outlook

The consideration of a long-term perspective on the behaviour of the peatland functions is essential for an implementation of sustainable land use strategies. With PMDSS, a gap was filled among the variety of existing DSSs and models which are focused on different aspects of peatland investigations and management at different temporal and spatial scales. In contrast, often simple estimations are made by practitioners in the field. The model approach of PMDSS is based on a comprehensive set of indicators of peatland functions (harvest of plant products, land use category, mean summer water table, nitrogen discharge, Global Warming Potential, conservation value of plants) and includes the simulation of the interactions between the system components (subsidence, land use, carbon, nitrogen, Global Warming Potential, vegetation, hydrology).

PMDSS is thought to be a valuable model for its application during the initial decision making process about peatland management targets. It is applicable to minerotrophic peatland sites in Europe which are used for agriculture, forestry, nature conservation, and abandoned land. Due to adjustment possibilities, the model can be adapted to various regional and site specific conditions. Without adjustments, PMDSS is at present applicable to minerotrophic peatland sites in northern Germany which have been drained already for at least 7 years, with medium or low nitrogen availability and for hydrological conditions without upward groundwater seepage and without fast surface runoff.

Although PMDSS is easy to use, some background knowledge of the subject as well as some insight into the functionality of the model is needed. Thus, it is recommended that PMDSS is applied by a model expert together with the relevant decision-makers and stakeholders. The application of PMDSS in the decision making process about peatland management may support the general understanding of the peatland ecosystem, the consideration of all peatland functions, and the integration of the main stakeholders with their different interests. Moreover, the application of PMDSS can make the assumptions for a decision for a specific management target documented and reproducible. Simulation results are to be interpreted as potential development trend of the peatland site.

Before implementing management measures in order to achieve management targets evaluated with PMDSS, further detailed investigations about the peatland characteristics are necessary in order to examine their feasibility. Furthermore, a monitoring program is recommended to follow if the selected management target will be achieved and to be able to adjust management measures. Recommended measures are:

- Vegetation and animal surveys in order to identify protected plant groups/ species and protected animal species
- Examination of potential for reestablishment of target species if priority is set to conservation and restoration
- Examination of geo-hydrological situation if increase in water table or rewetting is aimed
- Measurements of N-discharge rates for better evaluation

Suggestions for possible improvements of PMDSS and further implementations are given in the following

paragraphs. They result from the evaluation and discussion of the case studies (chapter 6) and the limits of PMDSS pointed out in the last sections. Recommendations for improving the application area are listed, suggestions for enhancing the representation of peatland functions are presented, and basic approaches for improving userfriendliness are proposed.

1. Based on the discussed limits of the application area, the following improvements of PMDSS are recommended:

- Parameter changes in the nitrogen module in order to get lower N-discharge rates at peat soils with high nitrogen availability (details see chapter 6.3.8)
- Extension of the temperature factor TF with precipitation to enhance the representation of climatical influence on the parameters subsidence rate, CO₂-emission, CH₄-emission, and N-mineralization, e.g. by using the LANG factor (EGGELSMANN 1976, compare chapter 4.3.1.1)
- Introduction of the influence of changing evapotranspiration rates with tree development on peatland hydrology (PRICE *et al.* 2003)
- Including higher subsidence rates after first drainage or redrainage (compare adjustment of PMDSS for the Swedish redrainage scenario, chapter 6.3.4) using the equations 4.1 to 4.3
- Calibration and validation of conservation value development for other countries than Germany

2. For enhanced representation of peatland functions, the following model extensions might be useful:

- Inclusion of a phosphorus module
- Extension of the hydrology module with the possibility of changing groundwater seepage and climatical water balance with time (detailed discussion in chapter 6.3.8)
- The addition of further biodiversity indices, especially to account for other species groups than plants

3. The userfriendliness and understandability of PMDSS can be improved with the following suggestions (discussed in detail in chapter 6.3.8):

- Extension of text output for result explanations and recommendations for management
- Classification of indicators into categories (such as high, middle, low) to be used in the input and results worksheets
- Inclusion of further input restrictions to prevent input mistakes
- Indication of result uncertainties in the model output

In the course of further development and improvement of PMDSS, it is important to keep the balance between simplicity, complexity, and transparency (GOOSEN *et al.* 2007). The aim of a user-friendly and understandable decision support system should be maintained (see discussion of userfriendliness in the paragraph on page 116). Despite its inherent limitations, reasonable results can be achieved with PMDSS as discussed in the previous section. Furthermore, PMDSS reached a state of development where its application in the context of sustainable peatland management may enhance the understanding of the functioning and future development of the considered peatland ecosystems and support stakeholders within their decision making process about the management of peatlands.

7 *Discussion and conclusion*

8 Summary

A semi-quantitative decision support system to predict long-term changes of peatland functions was developed. The system is called Peatland Management Decision Support System (PMDSS). Its aim is to support the implementation of sustainable land use strategies in Europe. PMDSS is designed to support scientists, water boards, and environmental agencies in decision making processes for long-term management of peatlands. Application areas are minerotrophic peatland sites in Western, Central, and Northern Europe used for agriculture, forestry, nature conservation, as well as abandoned land. The objectives of PMDSS are the definition of realistic management targets for peatlands, the demonstration of long-term changes and interactions of peatland functions, and the support of sustainable use, conservation, and restoration of peatlands. The study is part of the European project EUROPEAT.

The study is based on a multifunctional approach, where ecosystem functions are differentiated into production function, carrier function, regulation function, and informational function. For peatland ecosystem functions, indicators were selected which are used as output parameters of the model: harvest of plant products, land use category, mean summer water table, nitrogen discharge, Global Warming Potential, and conservation value of plants. The indicators represent the main problems of agricultural peatland use and are transferable into PMDSS. PMDSS is implemented as an one-dimensional mathematical computer model in the spreadsheet program Excel. The spatial resolution is set to site scale. A site is defined as an area with homogeneously distributed model parameters (e.g. land use category, vegetation type, summer water table). The model operates with annual time steps for a time span of 100 years. The vegetation development is calculated for 50 years. For the calculations of indicators and additional parameters, PMDSS is divided into seven modules: subsidence, land use, carbon, nitrogen, Global Warming Potential, vegetation, and hydrology. Qualitative and quantitative knowledge is included in the modules with regression equations, simple rules, a Markov chain model, and analytical equations. PMDSS includes continuous changes of peatland sites due to subsidence and consequent vegetation adaptation. Changes in the forcing functions land use and water management may cause abrupt system changes. The amount of input parameters is reduced to parameters easily collectable within a few days and with low costs. The results of the model (indicators, additional parameters) are presented in form of value tables, text output, and visualized as time series and in an amoeba diagram. They give a rough estimate for the development trend of a peatland site.

The applicability of PMDSS was tested in three case studies: (1) a peatland site in the Eider Valley, Germany, (2) the peatland Mötjerpolder, Germany, (3) sites of EUROPEAT partner countries. The results show that effects of changes in land use and water management as well as global climate change on the development of peatland functions may vary depending on the initial situation of the specific sites. Overall, PMDSS gives reasonable results. Due to the adjustment possibilities, PMDSS is well suited to be adapted to different regional and site specific conditions in Europe. The model is best valid for peatland sites in northern Germany. The application of PMDSS in the decision-making process about peatland management can support the general understanding of the peatland ecosystem, the consideration of all peatland functions, and the involvement of the main stakeholders with their multiple perceptions interests and knowledge. Thus, PMDSS has the potential to support the sustainable and wise use of peatlands. Moreover, the application of PMDSS makes the decision for a management target documented and reproducible.

9 Zusammenfassung

Es wurde das semi-quantitative Entscheidungsunterstützungssystem PMDSS (Peatland Management Decision Support System) entwickelt, welches langfristige Entwicklungstrends für Moorökosysteme vorhersagt. Mit diesem Modell soll die Umsetzung nachhaltiger Landnutzungsstrategien in Europa unterstützt werden. PMDSS kann Anwendergruppen, wie Wissenschaftler, Wasser- und Bodenverbände und Umweltämter in ihren Entscheidungsprozessen beim langfristigen Management von Moorböden unterstützen. Anwendungsgebiete sind Niedermoorflächen in West-, Zentral- und Nordeuropa, die für Landwirtschaft, Forstwirtschaft oder Naturschutz genutzt werden, sowie für brach gefallene Flächen. Ziele des PMDSS sind die Definition realistischer Managementziele, die Abbildung langfristiger Änderungen von Moorfunktionen und der Wechselwirkungen zwischen diesen, sowie die Unterstützung nachhaltiger Nutzung, des Schutzes und der Restaurierung von Moorökosystemen. Die Arbeit wurde im Rahmen des EU-Projektes EUROPEAT durchgeführt.

Die Modellentwicklung basiert auf dem multifunktionalen Ansatz, bei dem die Ökosystemfunktionen in Produktionsfunktion, Trägerfunktion, Regulationsfunktion und Informationsfunktion unterschieden werden. Für die Ökosystemfunktionen von Moorböden wurden Indikatoren ausgewählt, die als Ergebnisgrößen für das Modell übernommen wurden: Ernte pflanzlicher Produkte, Landnutzungskategorie, mittlerer Sommerwasserstand, Stickstoffaustrag, Klimawirksamkeit (Global Warming Potential) und Naturschutzwert der Pflanzen. Die Indikatoren decken die wichtigsten Probleme landwirtschaftlicher Nutzung von Moorböden ab. PMDSS ist ein ein-dimensionales Modell, bestehend aus einer Excel-Datei. Es ist für eine Fläche anwendbar, für die die Modellparameter wie Landnutzungskategorie, Vegetationstyp und mittlerer Sommerwasserstand als homogen angenommen werden können. PMDSS modelliert mit jährlichen Intervallen und über eine Zeitspanne von 100 Jahren (Vegetationsentwicklung 50 Jahre). Für die Berechnung der Indikatoren und zusätzlicher Parameter ist das Modell in sieben Module unterteilt: Sackung, Landnutzung, Kohlenstoff, Stickstoff, Klimawirksamkeit, Vegetation und Hydrologie. In den Modulen wird qualitatives und quantitatives Wissen durch Regressionsgleichungen, einfache Regeln, einem Markov-Ketten Modell und analytischen Gleichungen abgebildet. PMDSS kann kontinuierliche Systemänderungen von Moorböden durch Sackung und Sukzession modellieren. Abrupte Systemänderungen werden durch Änderung von Landnutzung und Wasser-Management hervorgerufen. Die Eingangsdaten sind innerhalb weniger Tage und unter geringem Kostenaufwand zu erheben. Die Modellergebnisse (Indikatoren und zusätzliche Parameter) werden als Werte in Tabellen, als Text und graphisch in Zeitreihen, sowie in einem Amoeba-Diagramm ausgegeben. Sie sind als grobe Schätzung der Entwicklungsrichtung der Moorfunktionen der untersuchten Fläche zu interpretieren.

Die Anwendbarkeit von PMDSS wurde in drei Fallstudien getestet: (1) eine Fläche im Eidertal in Deutschland, (2) das Niedermoorgebiet Mötjenspolder in Deutschland und (3) Flächen aus Ländern der EUROPEAT Projektpartner. Die Ergebnisse zeigen, dass sich Änderungen der Landnutzung und des Wasser-Managements, sowie globale Klimaänderungen, in Abhängigkeit von der Ausgangssituation der untersuchten Fläche, unterschiedlich auf die Entwicklung der Moorfunktionen auswirken. PMDSS ist mit Einstellungsoptionen ausgestattet, mit denen es an regional unterschiedliche Systemeigenschaften angepasst werden kann. Am besten ist das Modell an Moorböden in Norddeutschland angepasst. Der Einsatz von

PMDSS in Entscheidungsprozessen für Managementziele von Moorböden kann das allgemeine Verständnis von Moorökosystemen, die Betrachtung aller Moorfunktionen und die Einbeziehung der unterschiedlichsten Stakeholder mit ihren Interessen unterstützen. Daher hat PMDSS das Potential, die nachhaltige Nutzung von Moorböden zu unterstützen. Darüber hinaus kann die Entscheidungsgrundlage für ein Managementziel durch die Anwendung von PMDSS dokumentiert und nachvollzogen werden.

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Appendix

A Glossary

Term	Description	Source
AMOEBBA	Dutch acronym for 'a general method of ecosystem description and assessment'	TEN BRINK <i>et al.</i> (1991)
Bog	Mire raised above the surrounding landscape and only fed by precipitation.	JOOSTEN & CLARKE (2002)
Fen	Mire which in addition to precipitation water also receives water that has been in contact with mineral soil or bedrock.	adapted from JOOSTEN & CLARKE (2002)
Ecosystem functions	The support of material and non-material life of human beings by an ecosystem.	adapted from JOOSTEN & CLARKE (2002)
Ecosystem services	The benefits people obtain from ecosystems.	MA (2005a)
Global Warming Potential (GWP)	An index, describing the radiative characteristics of well-mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.	http://www.ipcc.ch/pub/syrgloss.pdf
Minerotrophic peatland	Peatland which in addition to precipitation water also receives water that has been in contact with mineral soil or bedrock.	
Mire	A peatland where peat is currently being formed and accumulating.	JOOSTEN & CLARKE (2002)
Ombrotrophic peatland	Peatland raised above the surrounding landscape and only fed by precipitation.	
Peatland	An area with or without vegetation with a naturally accumulated peat layer at the surface with a minimum peat thickness of 30 cm and a minimum content of dead organic material (dry mass) of 30%.	JOOSTEN & CLARKE (2002), AG BODEN (1994)
Semi-quantitative model	Model including qualitative and quantitative knowledge.	BERLEANT & KUIPERS (1997)

A Glossary

(continuation of the glossary)

Term	Description	Source
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.	WCED (1987)
Transitional fen	Mires, intermediate between fen and bog.	
Vegetation relevee	List of species and their coverage within a defined unit.	
Wetland	Generally wetlands have the presence of shallow water or flooded soils for part of the growing season, have organisms adapted to this wet environment, and have soil indicators of this flooding such as hydric soils.	MITSCH & GOSSELINK (2000a)
Wise use	Wise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development. Ecological character is the combination of the ecosystem components, processes and benefits/ services that characterise the wetland at a given point in time.	RAMSAR CONVENTION SECRETARIAT (2007)

B Symbol list

Symbol	Unit	Description
<i>a</i>	-	Factor dependent on bulk density (equations 4.2, SEGEBERG 1960)
<i>A</i>	-	Factor dependent on bulk density (equations 4.1, SEGEBERG 1960)
<i>ANAER</i>	cm	Anaerobic peat layer
<i>BIO</i>	t dry matter ha ⁻¹ a ⁻¹	Dying biomass after rewetting
<i>CH4_C</i>	kg CH ₄ -C ha ⁻¹ a ⁻¹	CH ₄ -emission
<i>Cl</i>	cm	Clay layer thickness near surface
<i>cons_{pg}</i>	-	Conservation value of a plant group
<i>conv</i>	kg N/ t dry matter	Conversion factor used in nitrogen module
<i>COV_{avpg}</i>	-	Average coverage of all vegetation types for a plant group
<i>COV_{sp}</i>	%	Cover of plant species
<i>COV_{pg}</i>	0 - 1	Coverage of plant group
<i>COV_{stpg}</i>	0 - 1	Coverage of plant group in starting year
<i>COV_{tarpg}</i>	0 - 1	Coverage of plant group in target vegetation type
<i>CO2_C</i>	kg CO ₂ -C ha ⁻¹ a ⁻¹	CO ₂ -emission
<i>CO2_C_{Renger}</i>	kg CO ₂ -C ha ⁻¹ a ⁻¹	CO ₂ -emission in equation 4.16 (RENGER <i>et al.</i> 2002)
<i>D_a</i>	m	Distance from site centre to boundary a of the sector (quadrangle, circle)
<i>D_b</i>	m	Distance from site centre to boundary b of the sector (quadrangle)
<i>D_c</i>	m	Distance from site centre to boundary c of the sector (quadrangle, parallel flow)
<i>D_d</i>	m	Distance from site centre to boundary d of the sector (quadrangle, parallel flow)
<i>DIFF</i>	kg N ha ⁻¹ a ⁻¹	= NINP - NPRO
<i>DPT</i>	mm a ⁻¹	Decrease of peat thickness (equations 4.6, RENGER <i>et al.</i> 2002)
<i>fn</i>	-	Factor for calculation of NDE, NE, NDIS
<i>fg_h</i>	-	Factor for calculation of GWP for time horizon <i>h</i>
<i>F_{CO_{pg}}</i>	-	Conversion factor of a plant group to multiply with coverage get standing crop

B Symbol list

(continuation of the symbol list)

Symbol	Unit	Description
Fta_{pg}	-	Target factor of a plant group to multiply with coverage get standing crop
GWP	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential
GWP_{20}	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential for the time horizon of 20 years
GWP_{100}	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential for the time horizon of 100 years
GWP_{500}	kg CO ₂ -C-equ. ha ⁻¹ a ⁻¹	Global Warming Potential for the time horizon of 500 years
h_{sp}	cm	Average height of a plant species
H_a	m ASL	Mean summer water table at boundary a of the sector (quadrangle, circle)
H_b	m ASL	Mean summer water table at boundary b of the sector (quadrangle)
H_c	m ASL	Mean summer water table at boundary c of the sector (quadrangle, parallel flow)
H_d	m ASL	Mean summer water table at boundary d of the sector (quadrangle, parallel flow)
HAR	t dry matter ha ⁻¹ a ⁻¹	Harvest of plant products
HC	m ASL	Mean summer water table at the sector centre
HC_0	m ASL	Theoretical water table without net recharge of sector centre
HC_m	m	Groundwater mound of mean summer water table at sector centre
H_{bal}	m ASL	Bottom of the aquifer layer
Hr	m	Mean thickness of the water column without groundwater mound in the rectangle
HS	m ASL	Mean summer water table of the site centre
HS_0	m ASL	Theoretical water table without net recharge at site centre
HS_m	m	Groundwater mound of the summer water table at site centre
i	-	Indicator
k	-	Factor dependent on bulk density (equations 4.3, SEGEBERG 1960)
$ksat$	m/ d	Mean saturated hydraulic conductivity of the soil profile
$ksat_1$	m/ d	Mean saturated hydraulic conductivity of the soil layer 1
$ksat_2$	m/ d	Mean saturated hydraulic conductivity of the soil layer 2
$ksat_3$	m/ d	Mean saturated hydraulic conductivity of the soil layer 3
L	m	Distance between boundary c and d (parallel flow)
L_1	m	Length of the longer boundary of the rectangle, calculated from the quadrangle

(continuation of the symbol list)

Symbol	Unit	Description
L_2	m	Length of the shorter boundary of the rectangle, calculated from the quadrangle
L_a	m	Length of boundary a of the sector (quadrangle, circle)
L_b	m	Length of boundary b of the sector (quadrangle)
L_c	m	Length of boundary c of the sector (quadrangle, parallel flow)
L_d	m	Length of boundary d of the sector (quadrangle, parallel flow)
LU	1 - 12	Land use category
LUF	-	Land use factor
M	mm a ⁻¹	Subsidence, mainly due to mineralization (equation 4.5, BLANKENBURG <i>et al.</i> 2001)
M_1	m	Thickness of soil layer 1
M_2	m	Thickness of soil layer 2
M_3	m	Thickness of soil layer 3
n	-	Amount of species with red list status within a plant group
n_i	-	Conversion number, used to calculate relative change of indicators
N	m/ a	Net recharge rate
$NAVA$	kg N ha ⁻¹ a ⁻¹	Available nitrogen for biomass production
NC	mg/ l	Nitrogen concentration in precipitation
NDE	kg N ha ⁻¹ a ⁻¹	N ₂ O-emission
$NDEP$	kg N ha ⁻¹ a ⁻¹	Nitrogen deposition (wet + dry)
$NDIS$	kg N ha ⁻¹ a ⁻¹	Nitrogen discharge (NO ₃ , NH ₄ , DON)
NE	kg N ha ⁻¹ a ⁻¹	N ₂ -emission
$NFER$	kg N ha ⁻¹ a ⁻¹	Nitrogen fertilizer
$NFIX$	kg N ha ⁻¹ a ⁻¹	Nitrogen fixation by plants
$NHAR$	kg N ha ⁻¹ a ⁻¹	Nitrogen content in harvested biomass
$NIMM$	kg N ha ⁻¹ a ⁻¹	Immobilized nitrogen
$NINP$	kg N ha ⁻¹ a ⁻¹	Summarized nitrogen of the inflow pathways (= NDEP + NFIX + NFER + NMIN)
$NMIN$	kg N ha ⁻¹ a ⁻¹	Nitrogen mineralization
$NMIN_{Renger}$	kg N ha ⁻¹ a ⁻¹	Nitrogen mineralization in equation 4.21 (RENGER <i>et al.</i> 2002)
$NPRO$	kg N ha ⁻¹ a ⁻¹	Nitrogen content in biomass production
$NPRO_{pot}$	kg N ha ⁻¹ a ⁻¹	Potential nitrogen content in biomass production
PG	mm/ a	Peat growth (equation 4.5, BLANKENBURG <i>et al.</i> 2001)

B Symbol list

(continuation of the symbol list)

Symbol	Unit	Description
<i>PH</i>	-	Proportion of harvest of standing crop production
<i>PRE</i>	mm/ a	Mean annual precipitation
<i>PT</i>	cm, m	Peat thickness
<i>PTaw</i>	cm, m	Peat thickness above summer water table
<i>PTbw</i>	cm, m	Peat thickness below summer water table
<i>qCWB</i>	m/ a	Climatic water balance of summer (= precipitation - evapotranspiration)
<i>qET</i>	m/ a	Evapotranspiration
<i>qFEX</i>	m/ a	Flood exchange
<i>qGWS</i>	m/ a	Groundwater seepage (upward and downward)
<i>qP</i>	m/ a	Precipitation
<i>qSSWI</i>	m/ a	Subsurface water inflow (interflow, drains and pipes, near-surface groundwater)
<i>qSSWO</i>	m/ a	Subsurface water outflow (tube flow, subsurface outflow),
<i>qSWI</i>	m/ a	Surface water inflow (surface runoff, ditch inflow, well inflow)
<i>qSWO</i>	m/ a	Surface water outflow (surface runoff, ditch outflow),
<i>Q₁₀</i>	-	Factor by which the respiration rate differs for a temperature interval of 10°C
<i>R</i>	m	Radius of the circle
<i>R_{i,1}</i>	-	Relative value of the initial state of indicator <i>i</i>
<i>R_{i,50}</i>	-	Relative value of indicator <i>i</i> 50 years later
<i>S</i>	m	Subsidence of soil surface (equations 4.1 to 4.3, SEGEBERG 1960)
<i>SC_{avpg}</i>	t dry matter ha ⁻¹ a ⁻¹	Average standing crop of all vegetation types for a plant group
<i>SC_{pg}</i>	t dry matter ha ⁻¹ a ⁻¹	Standing crop of a plant group
<i>SC_{vt}</i>	t dry matter ha ⁻¹ a ⁻¹	Average standing crop of a vegetation type
<i>SCPRO</i>	t dry matter ha ⁻¹ a ⁻¹	Production of standing crop biomass
<i>SF</i>	-	Subsidence factor
<i>SUB</i>	cm/ a	Subsidence rate of surface
<i>SUBan</i>	cm/ a	Subsidence rate of anaerobic peat layer
<i>SWT</i>	cm below surface or cm	Mean summer water table or depth to mean summer water table
<i>SWT_{ASL}</i>	m ASL	Mean summer water table of the site
<i>SWT_{fl}</i>	cm	Mean summer water table fluctuations, standard deviation of summer water table of the site

(continuation of the symbol list)

Symbol	Unit	Description
t	m	Depth to water table after subsidence (equations 4.1, SEGEBERG 1960)
tn	m	Depth of drains after subsidence (equations 4.3, SEGEBERG 1960)
tp_{pg}	-	Transition probability of a plant group
T	°C	Air temperature
T_S	m	Thickness of peat layers before drainage (equations 4.1 to 4.3, SEGEBERG 1960)
TF	-	Temperature factor
$V_{i,1}$		Value of the of indicator i in the initial state
$V_{i,50}$		Value of indicator i after a simulation of 50 years
$WRLS_{sp}$	-	Weighted red list status of plant species
xu	m	Distance of site centre to sector centre in x direction in the rectangle
y	year	Expected time for change in coverage of a plant group
yu	m	Distance of site centre to sector centre in y direction in the rectangle
$\Delta V / \Delta t$	volume per time	Change in water storage in peat soil per unit time
Φ	-	Geohydraulic potential

C Plant species list

Plant species list with their attribution to plant groups, used in vegetation module, their red list status and plant height.

Species name	Abandonment category	Intensification category	Water source	Water table	Red lists ^d						mid. Plant height in cm	
					Germany	Netherlands	Norway	Poland	Sweden	Great Britain		
Acorus calamus			M	F	MF	10	10	10	10	10	10	90
Acer pseudoplatanus juv.	D	F	M	D	DFMD	10	10	10	10	10	10	5
Achillea millefolium agg.	A	CE	M	D	ACEMD	10	10	10	10	10	10	32.5
Achillea ptarmica	A	CM	R	D	ACMRD	10	10	10	10	10	10	60
Adoxa moschatellina	D	F	G	D	DFGD	10	10	10	10	10	10	10
Aegopodium podagraria	D		G	D	DGD	10	10	10	10	10	10	32.5
Agrostis canina	B	CM	R	D	BCMRD	10	10	10	10	10	10	45
Agrostis capillaris	A	RA	R	D	ARARD	10	10	10	10	10	10	40
Agrostis gigantea			M	D	MD	10	10	10	10	10	10	100
Agrostis stolonifera	B	RA	M	D	BRAMD	10	10	10	10	10	10	24
Ajuga reptans	C	CE	M	D	CCEMD	10	10	E	10	10	10	18.5
Alchemilla vulgaris	A	CE	M	D	ACEMD	10	10	10	10	10	10	40
Alisma plantago-aquatica			M	F	MF	10	10	10	10	10	10	100
Alnus glutinosa	D	F1	M	D	DF1MD	10	10	10	10	10	10	1350
Alopecurus aequalis	A	RA	G	D	ARAGD	10	10	10	10	10	10	30
Alopecurus geniculatus	B	RA	G	D	BRAGD	10	10	10	10	10	10	30
Alopecurus pratensis	D	CE	M	D	DCEMD	10	10	10	10	10	10	75
Anagallis arvensis	A	O	M	D	AOMD	10	10	10	10	10	10	22.5
Anemone nemorosa	D	F	M	D	DFMD	10	10	10	10	10	10	15
Angelica archangelica	C	SC	M	D	CSCMD	10	10	10	10	10	10	170
Angelica sylvestris	C	CE	M	D	CCEMD	10	10	10	10	10	10	105
Anthoxanthum odoratum	A	CM	M	D	ACMMD	10	10	10	10	10	10	45
Anthriscus sylvestris	C	CE	M	D	CCEMD	10	10	10	10	10	10	105
Apera spica-venti	A	O	M	D	AOMD	10	10	10	10	10	10	115
Aphanes arvensis	A	O	M	D	AOMD	10	EN	10	10	10	10	12.5
Aphanes microcarpa	A	O	M	D	AOMD	10	10	10	10	10	10	10
Arenaria serpyllifolia	A	O	M	D	AOMD	10	10	10	10	10	10	15
Arrhenatherum elatius	A	CE	M	D	ACEMD	10	10	10	10	10	10	100
Artemisia vulgaris	A	O	M	D	AOMD	10	10	10	10	10	10	90
Athyrium filix-femina	D		M	D	DMD	10	10	10	10	10	10	40
Atriplex hastata	D	O	M	D	DMD	10	10	R	10	10	10	50
Avena sativa	A	O	M	D	AOMD	10	10	10	10	10	10	90
Avenella flexuosa	D		M	D	DMD	10	10	10	10	10	10	50
Avenochloa pubescens	A	CE	M	D	ACEMD	10	10	10	10	10	10	60
Bellis perennis	A	RA	M	D	ARAMD	10	10	10	10	10	10	10
Berula erecta	C	CM	M	F	CCMMF	10	10	EN	10	10	10	45
Betula humilis	D	F	R	D	DFRD	V	10	10	EN	10	10	175
Betula pendula	D	F	M	D	DFMD	10	10	10	10	10	10	1800
Betula pubescens	D	F	R	D	DFRD	10	10	10	10	10	10	1050
Bidens cernua	C	RA	M	D	CRAMD	10	10	DC	10	10	10	52.5
Bidens tripartita	A	RA	M	D	ARAMD	10	10	10	10	10	10	60
Blysmus compressus	A	CM	G	D	ACMGD	V	VU	E	10	10	10	27.5
Bolboschoenus maritimus			G	F	GF	10	10	10	10	10	10	82.5
Brassica napus	A	O	M	D	AOMD	10	10	10	10	10	10	90

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table		Red lists ^a						mid. Plant height in cm
						Germany	Netherlands	Norway	Poland	Sweden	Great Britain	
Briza media	A	SC	M	D	ASCMD	10	10	10	10	10	10	35
Bromus hordeaceus	A	RA	M	D	ARAMD	10	10	10	10	10	10	52.5
Bromus racemosus	A	CE	M	D	ACEMD	R	VU	10	VU	EN	10	60
Calamagrostis canescens	D	CM	M	D	DCMMD	10	10	10	10	10	10	105
Calamagrostis stricta	A	SC	M	D	ASCMD	10	EN	10	10	10	NT	65
Calla palustris			M	D	MD	R	10	10	10	10	10	22.5
Calluna vulgaris	D		M	R	DMR	10	10	10	10	10	10	65
Caltha palustris	C	CM	M	D	CCMMD	10	10	10	10	10	10	32.5
Capsella bursa-pastoris	A	O	M	D	AOMD	10	10	10	10	10	10	32.5
Cardamine amara	D	CE	M	D	DCEMD	10	10	10	10	10	10	30
Cardamine flexuosa			M	D	MD	10	10	10	10	10	10	22.5
Cardamine pratensis agg.	B	RA	M	D	BRAMD	10	10	10	10	10	10	32.5
Carex acuta	D	CE	M	D	DCEMD	10	10	10	10	10	10	100
Carex acutiformis	D	CE	G	D	DCEGD	10	10	DC	10	10	10	75
Carex appropinquata	B	SC	G	D	BSCGD	V	V	10	10	10	10	60
Carex buxbaumii	A	SC	G	D	ASCGD	V	R	10	VU	10	NT	50
Carex canescens	B	CM	R	D	BCMMD	10	10	10	10	10	10	35
Carex chordorrhiza	B	SC	R	D	BSCRD	V	10	10	VU	10	V	17.5
Carex cespitosa	D	CE	M	D	DCEMD	R	R	10	10	10	10	40
Carex davalliana	A	SC	G	D	ASCGD	R	10	10	VU	10	EX	25
Carex demissa	A	SC	R	D	ASCRD	10	10	10	10	10	10	16.5
Carex diandra	A	SC	M	D	ASCMD	V	VU	10	EN	10	10	45
Carex dioica	A	SC	M	D	ASCMD	V	CR	10	EN	10	10	17.5
Carex disticha	D	CM	G	D	DCMMD	10	10	10	10	10	10	57.5
Carex echinata	B	SC	R	D	BSCRD	10	10	10	10	10	10	20
Carex elata	D	SC	M	F	DSCMF	10	10	DC	10	10	10	75
Carex elongata	D		G	D	DGD	10	10	10	10	10	10	45
Carex elytroides			M	D	MD	10	10	10	10	10	10	60
Carex flacca	A	SC	G	D	ASCGD	10	10	10	10	10	10	35
Carex flava	A	SC	G	D	ASCGD	10	EN	10	10	10	V	35
Carex hirta	A	CE	M	D	ACEMD	10	10	10	10	10	10	40
Carex hostiana	A	SC	M	D	ASCMD	V	EN	10	10	10	10	40
Carex lasiocarpa	B	SC	R	D	BSCRD	R	VU	10	10	10	10	65
Carex lepidocarpa	A	SC	G	D	ASCGD	V	EN	10	10	10	10	30
Carex limosa	A	SC	R	D	ASCRD	V	EX	10	VU	10	10	35
Carex nigra	B	CM	R	D	BCMMD	10	10	10	10	10	10	37.5
Carex otrubae	A	SC	M	D	ASCMD	10	10	10	10	10	10	45
Carex ovalis (leporina)	A	CE	R	D	ACERD	10	10	10	10	10	10	40
Carex pallescens			M	D	MD	10	10	10	10	10	10	35
Carex panicea	B	SC	M	D	BSCMD	10	10	10	10	10	10	30
Carex paniculata	D	CM	G	D	DCMMD	10	10	DC	10	10	10	75
Carex pseudocyperus	D	SC	M	F	DSCMF	10	10	DC	10	10	10	75
Carex pulicaris	A	SC	M	D	ASCMD	V	EN	10	VU	10	10	15
Carex remota	D	F	M	D	DFMD	10	10	10	10	10	10	45
Carex riparia	D	CE	G	D	DCEGD	10	10	V	10	10	10	90
Carex rostrata	B	CM	R	F	BCMRF	10	10	10	10	10	10	45
Carex vesicaria	D	CM	M	D	DCMMD	10	10	10	10	10	10	75
Carpinus betulus	D	F	M	D	DFMD	10	10	10	10	10	10	1550
Centaurea cyanus	A	O	M	D	AOMD	10	R	10	10	10	EN	45
Centaurea jacea	A	SC	M	D	ASCMD	10	10	10	10	10	10	65
Cerastium holosteoides	B	RA	M	D	BRAMD	10	10	10	10	10	10	24.5
Chaerophyllum hirsutum			M	D	MD	10	10	10	10	10	10	85
Chaerophyllum temulum	A	O	M	D	AOMD	10	10	10	10	10	10	75
Chenopodium album	A	O	M	D	AOMD	10	10	10	10	10	10	65.5
Chenopodium polyspermum	A	O	M	D	AOMD	10	10	10	10	10	10	45

C Plant species list

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table	Red lists ^a						mid. Plant height in cm	
					Germany	Netherlands	Norway	Poland	Sweden	Great Britain		
Chrysosplenium alternifolium	D	F	G	D	DFGD	10	10	10	10	10	10	10
Chrysosplenium oppositifolium	D		M	D	DMD	10	10	10	10	CR	10	7.5
Cicuta virosa	D	CM	M	D	DCMMD	R	10	10	10	10	10	90
Circaea lutetiana	D		G	D	DGD	10	10	10	10	10	10	45
Cirsium arvense	D	RA	M	D	DRAMD	10	10	10	10	10	10	90
Cirsium oleraceum	C	CE	G	D	CCEGD	10	R	DC	10	10	10	105
Cirsium palustre	B	CM	R	D	BCMRD	10	10	10	10	10	10	105
Cirsium vulgare	D	RA	G	D	DRAGD	10	10	10	10	10	10	90
Cladium mariscus	D		G	F	DGF	R	VU	V	10	10	10	135
Conium maculatum	A	O	M	D	AOMD	10	10	10	10	10	10	120
Convallaria majalis	D	F	M	D	DFMD	10	10	10	10	10	10	22.5
Convolvulus arvensis	A	O	M	D	AOMD	10	10	10	10	10	10	70
Corylus avellana	D	F	M	D	DFMD	10	10	10	10	10	10	350
Crataegus laevigata	D	F	G	D	DFGD	10	10	10	10	10	10	315
Crataegus monogyna	D	F	G	D	DFGD	10	10	10	10	10	10	315
Crepis paludosa	C	SC	G	D	CSCGD	10	10	10	10	10	10	75
Cynosurus cristatus	A	CE	M	D	ACEMD	10	10	10	10	10	10	40
Dactylis glomerata [s.l.]	B	CE	M	D	BCEMD	10	10	10	10	10	10	60
Dactylorhiza fuchsii	A	SC	M	D	ASCMD	10	10	10	VU	10	10	22.5
Dactylorhiza incarnata	A	SC	G	D	ASCMD	V	VU	10	EN	10	10	37.5
Dactylorhiza maculata [s.l.]	A	SC	M	D	ASCMD	R	VU	10	VU	10	10	37.5
Dactylorhiza majalis	B	SC	G	D	BSCGD	R	10	10	10	NT	10	37.5
Danthonia decumbens	A	SC	R	D	ASCRD	10	10	10	10	10	10	37.5
Deschampsia cespitosa	D	CE	M	D	DCEMD	10	10	10	10	10	10	90
Digitaria ischaemum	A	O	R	D	AORD	10	10	10	10	VU	10	27.5
Drosera rotundifolia	A	SC	R	D	ASCRD	R	R	10	VU	10	10	17.5
Dryopteris carthusiana	D	SC	R	D	DSCRD	10	10	10	10	10	10	55
Dryopteris cristata	D	SC	M	D	DSCMD	R	10	DC	VU	10	10	55
Dryopteris dilatata	D		M	D	DMD	10	10	10	10	10	10	75
Dryopteris filix-mas	D	F	M	D	DFMD	10	10	10	10	10	10	75
Eleocharis palustris	A	CM	M	F	ACMMF	10	10	10	10	10	10	35
Eleocharis quinqueflora	A	SC	G	D	ASCSD	V	EN	10	10	10	10	15
Eleocharis uniglumis	A	SC	G	D	ASCSD	10	10	10	10	10	10	25
Elymus repens	D	RA	M	D	DRAMD	10	10	10	10	10	10	75
Epilobium ciliatum	A	RA	M	D	ARAMD	10	10	10	10	10	10	60
Epilobium hirsutum	D	CE	G	D	DCEGD	10	10	10	10	10	10	105
Epilobium montanum	A	O	M	D	AOMD	10	10	10	10	10	10	45
Epilobium obscurum	C	CE	M	D	CCEMD	10	10	E	10	10	10	55
Epilobium palustre	C	CM	R	D	CCMRD	10	R	10	10	10	10	37.5
Epilobium parviflorum	B	CE	G	D	BCEGD	10	10	E	10	10	10	45
Epilobium roseum	C	CE	M	D	CCEMD	10	10	10	10	10	10	55
Epilobium tetragonum [s.l.]	A	CE	M	D	ACEMD	10	10	10	10	10	10	65
Epipactis palustris	A	SC	G	D	ASCSD	R	VU	V	VU	10	10	42.5
Equisetum arvense	D	CE	M	D	DCEMD	10	10	10	10	10	10	45
Equisetum fluviatile	C	CM	M	F	CCMMF	10	10	10	10	10	10	65
Equisetum palustre	B	CE	M	D	BCEMD	10	10	10	10	10	10	40
Equisetum sylvaticum	D	F	M	D	DFMD	10	10	10	10	10	10	45
Equisetum telmateia	D		G	D	DGD	10	10	10	10	CR	10	105
Erica tetralix	A	SC	R	D	ASCRD	10	10	10	10	10	10	35
Eriophorum angustifolium	B	SC	R	D	BSCRD	10	10	10	10	10	10	45
Eriophorum vaginatum	B	SC	R	D	BSCRD	10	VU	10	10	10	10	45
Erodium cicutarium	A	O	M	D	AOMD	10	10	10	10	10	10	32.5
Erysimum cheirantoides	A	O	G	D	AOGD	10	10	10	10	10	10	40
Euonymus europaea	D	F	G	D	DFGD	10	10	10	10	10	10	375
Eupatorium cannabinum	D	CM	G	D	DCMMD	10	10	DC	10	10	10	100

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table		Red lists ^a						mid. Plant height in cm
						Germany	Netherlands	Norway	Poland	Sweden	Great Britain	
<i>Euphorbia helioscopia</i>	A	O	G	D	AOGD	10	10	10	10	10	10	17.5
<i>Fagus sylvatica</i> juv.	D	F	M	D	DFMD	10	10	10	10	10	10	2700/5
<i>Festuca arundinacea</i>		O	G	D	OGD	10	10	10	10	10	10	125
<i>Festuca gigantea</i>		F	M	D	FMD	10	10	10	10	10	10	100
<i>Festuca pratensis</i>	D	RA	M	D	DRAMD	10	10	10	10	10	10	65
<i>Festuca rubra</i>	B	CM	M	D	BCMMD	10	10	10	10	10	10	55
<i>Filipendula ulmaria</i>	D	CE	M	D	DCEMD	10	10	10	10	10	10	90
<i>Frangula alnus</i>	D		R	D	DRD	10	10	10	10	10	10	450
<i>Fraxinus excelsior</i>	D		G	D	DGD	10	10	10	10	10	10	3000
<i>Fritillaria meleagris</i>	A	SC	G	D	ASCGD	V	EN	10	CR	10	10	35
<i>Fumaria officinalis</i>	A	O	M	D	AOMD	10	10	10	10	10	10	30
<i>Galeopsis bifida</i>	D	RA	M	D	DRAMD	10	10	10	10	10	10	35
<i>Galeopsis pubescens</i>	A	O	M	D	AOMD	10	CR	10	10	10	10	45
<i>Galeopsis tetrahit</i> agg.	D		M	D	DMD	10	10	10	10	10	10	45
<i>Galium aparine</i>	D	O	M	D	DOMD	10	10	10	10	10	10	90
<i>Galium hircynicum</i>	A	SC	R	D	ASCRD	10	10	10	10	10	10	18.5
<i>Galium palustre</i> [s.l.]	C	CM	M	D	CCMMD	10	10	10	10	10	10	27.5
<i>Galium uliginosum</i>	B	CM	M	D	BCMMD	10	10	10	10	10	10	37.5
<i>Geranium palustre</i>	A	SC	G	D	ASCGD	10	10	10	10	VU	10	27.5
<i>Geranium pusillum</i>	A	O	M	D	AOMD	10	10	10	10	10	10	22.5
<i>Geranium robertianum</i>	D		M	D	DMD	10	10	10	10	10	10	35
<i>Geum rivale</i>	C	CE	M	D	CCEMD	10	CR	10	10	10	10	30
<i>Geum urbanum</i>	D		M	D	DMD	10	10	10	10	10	10	45
<i>Glechoma hederacea</i> agg.	D	CE	M	D	DCEMD	10	10	10	10	10	10	37.5
<i>Glyceria declinata</i>	A	SC	M	D	ASCMD	10	10	V	10	10	10	40
<i>Glyceria fluitans</i>	B	RA	M	D	BRAMD	10	10	10	10	10	10	82.5
<i>Glyceria maxima</i>	D	CM	G	F	DCMGF	10	10	10	10	10	10	145
<i>Glyceria notata</i>	C	RA	G	F	CRAGF	10	10	E	10	10	10	52.5
<i>Gnaphalium uliginosum</i>	A	O	M	D	AOMD	10	10	10	10	10	10	12.5
<i>Hierochloa odorata</i>	A	SC	M	D	ASCMD	R	10	10	VU	10	NT	40
<i>Holcus lanatus</i>	B	CE	M	D	BCEMD	10	10	10	10	10	10	60
<i>Holcus mollis</i>		F	R	D	FRD	10	10	10	10	10	10	60
<i>Hordeum vulgare</i>	A	O	M	D	AOMD	10	10	10	10	10	10	90
<i>Hottonia palustris</i>	D		M	F	DMF	R	10	10	10	10	10	40
<i>Humulus lupulus</i>	D		M	D	DMD	10	10	10	10	10	10	325
<i>Hydrocotyle vulgaris</i>	B	SC	R	D	BSCRD	10	10	10	10	10	10	15
<i>Hypericum maculatum</i> agg.	C	SC	R	D	CSCRD	10	10	10	10	10	10	50
<i>Hypericum perforatum</i>		O	M	D	OMD	10	10	10	10	10	10	50
<i>Hypericum quadrangulum</i>	C	CE	G	D	CCEGD	10	10	10	10	NT	10	45
<i>Impatiens glandulifera</i>	D	O	M	D	DMD	10	10	10	10	10	10	130
<i>Impatiens noli-tangere</i>	D		G	D	DGD	10	10	10	10	10	10	50
<i>Iris pseudacorus</i>	D	CM	M	D	DCMMD	10	10	10	10	10	10	80
<i>Isolepis setacea</i>	A	O	M	D	AOMD	10	10	V	10	VU	10	11
<i>Juncus acutiflorus</i>	D	SC	M	D	DSCMD	10	10	E	10	10	10	40
<i>Juncus articulatus</i>	A	CM	M	D	ACMMD	10	10	10	10	10	10	40
<i>Juncus bufonius</i>	A	CM	R	D	ACMRD	10	10	10	10	10	10	19
<i>Juncus compressus</i>	A	CE	G	D	ACEGD	10	10	10	10	10	10	25
<i>Juncus conglomeratus</i>	A	SC	M	D	ASCMD	10	10	10	10	10	10	60
<i>Juncus effusus</i>	B	CM	R	D	BCMRD	10	10	10	10	10	10	60
<i>Juncus filiformis</i>	A	SC	R	D	ASCRD	10	VU	10	10	10	10	32.5
<i>Juncus inflexus</i>	A	CE	G	D	ACEGD	10	10	10	10	NT	10	60
<i>Juncus squarrosus</i>			R	D	RD	10	10	10	10	10	10	20
<i>Juncus subnodulosus</i>	D	SC	G	D	DSCGD	R	10	10	10	NT	10	85
<i>Lamium hybridum</i>	A	O	G	D	AOGD	10	10	10	10	10	10	20
<i>Lamium purpureum</i>	A	O	G	D	AOGD	10	10	10	10	10	10	18.5

C Plant species list

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table	Red lists ^d						mid. Plant height in cm	
					Germany	Netherlands	Norway	Poland	Sweden	Great Britain		
Lapsana communis	A	O	M	D	AOMD	10	10	10	10	10	10	75
Lathyrus palustris	A	SC	G	D	ASCGD	R	10	10	10	10	10	65
Lathyrus pratensis	A	CE	G	D	ACEGD	10	10	10	10	10	10	65
Lemna minor	D		M	F	DMF	10	10	10	10	10	10	0.1
Lemna trisulca	D		G	F	DGF	10	10	DC	10	10	10	3
Leontodon autumnalis	A	CM	M	D	ACMMD	10	10	10	10	10	10	26
Leontodon hispidus	A	SC	M	D	ASCMD	10	VU	DC	10	10	10	27.5
Liparis loeselii	A	SC	G	D	ASCGD	V	CR	Ex	VU	VU	EN	16
Listera ovata			G	D	GD	10	VU	10	10	10	10	32.5
Lolium multiflorum	B	RA	G	D	BRAGD	10	10	10	10	10	10	65
Lolium perenne	B	RA	M	D	BRAMD	10	10	10	10	10	10	50
Lonicera periclymenum	D	F	R	D	DFRD	10	10	10	10	10	10	250
Lotus uliginosus	B	CM	R	D	BCMRD	10	10	10	10	10	10	65
Luzula campestris	A	SC	R	D	ASCRD	10	10	10	10	10	10	12.5
Luzula multiflora	B	SC	M	D	BSCMD	10	10	10	10	10	10	30
Lychnis flos-cuculi	B	CM	M	D	BCMMD	10	10	10	10	10	10	60
Lycopus arvensis	A	O	M	D	AOMD	10	10	10	10	10	10	30
Lycopus europaeus	D	CE	M	D	DCEMD	10	10	10	10	10	10	60
Lysimachia nummularia	B	CM	M	D	BCMMD	10	10	10	10	10	10	35
Lysimachia thysiflora	C	SC	M	D	CSCMD	R	10	10	10	10	10	45
Lysimachia vulgaris	D	CM	M	D	DCMMD	10	10	10	10	10	10	105
Lythrum salicaria	C	CM	G	D	CCMGD	10	10	10	10	10	10	90
Maianthemum bifolium			R	D	RD	10	10	10	10	10	V	13.5
Matricaria chamomilla	A	O	M	D	AOMD	10	10	10	10	10	10	45
Matricaria matricarioides	A	O	M	D	AOMD	10	10	10	10	10	10	44
Medicago lupulina		O	G	D	OGD	10	10	10	10	10	10	28.5
Mentha aquatica	C	CM	G	D	CCMGD	10	10	10	10	10	10	60
Mentha arvensis	A	SC	M	D	ASCMD	10	10	10	10	10	10	30
Mentha x verticillata	B	CM	M	D	BCMMD	10	10	10	10	10	10	35
Menyanthes trifoliata	B	SC	M	D	BSCMD	R	R	10	10	10	10	22.5
Mercurialis perennis	D	F	G	D	DFGD	10	10	10	10	10	10	30
Moehringia trinervis			M	D	MD	10	10	10	10	10	10	22.5
Molinia caerulea	D	SC	M	D	DSCMD	10	10	10	10	10	10	75
Montia fontana [s.l.]	A	SC	R	D	ASCRD	10	10	10	10	10	10	22.5
Myosotis arvensis	A	O	M	D	AOMD	10	10	10	10	10	10	35
Myosotis scorpioides agg.	B	CE	M	D	BCEMD	10	10	10	10	10	10	30
Nardus stricta	A	SC	R	D	ASCRD	10	10	10	10	10	10	25
Oenanthe fistulosa	A	CE	G	D	ACEGD	R	10	10	10	EN	10	50
Ophioglossum vulgatum	A	SC	M	D	ASCMD	R	10	10	10	10	10	17.5
Oxalis acetosella			M	D	MD	10	10	10	10	10	10	7.5
Prunus avium	D	F	G	D	DFGD	10	10	10	10	10	10	1150
Parnassia palustris	A	SC	G	D	ASCGD	R	VU	10	10	10	10	22.5
Pedicularis palustris	A	SC	M	D	ASCMD	V	VU	10	10	10	10	32.5
Peucedanum palustre	C	CM	M	D	CCMMD	10	10	10	10	10	10	105
Phalaris arundinacea	D	CE	G	D	DCEGD	10	10	10	10	10	10	125
Phleum pratense agg.	D	RA	M	D	DRAMD	10	10	10	10	10	10	80
Phragmites australis	D	CM	G	F	DCMGF	10	10	10	10	10	10	200
Plantago lanceolata	A	CM	M	D	ACMMD	10	10	10	10	10	10	25
Plantago major	A	CE	M	D	ACEMD	10	10	10	10	10	10	30
Poa annua	B	RA	M	D	BRAMD	10	10	10	10	10	10	22.5
Poa palustris	A	CE	G	D	ACEGD	10	10	10	10	10	10	90
Poa pratensis agg.	B	RA	M	D	BRAMD	10	10	10	10	10	10	50
Poa trivialis [s.l.]	B	RA	M	D	BRAMD	10	10	10	10	10	10	70
Polygonum amphibium	B	CE	M	F	BCEMF	10	10	10	10	10	10	35
Polygonum aviculare	A	O	M	D	AOMD	10	10	10	10	10	10	50

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table		Red lists ^a						mid. Plant height in cm
						Germany	Netherlands	Norway	Poland	Sweden	Great Britain	
Polygonum bistorta	D	SC	M	D	DSCMD	10	10	10	10	10	10	55
Polygonum convolvulus	A	O	M	D	AOMD	10	10	10	10	10	10	25
Polygonum hydropiper	B	RA	M	D	BRAMD	10	10	10	10	10	10	50
Polygonum lapathifolium	A	RA	G	D	ARAGD	10	10	10	10	10	10	100
Polygonum persicaria	A	RA	M	D	ARAMD	10	10	10	10	10	10	60
Populus tremula	D	F	M	D	DFMD	10	10	10	10	10		1500
Potentilla anserina	A	CM	M	D	ACMMD	10	10	10	10	10	10	17.5
Potentilla erecta	B	SC	M	D	BSCMD	10	10	10	10	10	10	32.5
Potentilla palustris	B	SC	R	F	BSCRF	10	R	10	10	10	10	60
Potentilla reptans	B	SC	G	D	BSCGD	10	10	10	10	10	10	15
Primula elatior	D		G	D	DGD	10	10	10	10	10	10	22.5
Prunella vulgaris	B	CM	G	D	BCMGD	10	10	10	10	10	10	26
Prunus pardus	D	F	G	D	DFGD	10	10	10	10	10	10	900
Prunus serotina	D	F	M	D	DFMD	10	10	10	10	10	10	1150
Quercus robur	D	F	M	D	DFMD	10	10	10	10	10	10	2250
Ranunculus aconitifolius			M	D	MD	10	10	10	10	10	10	100
Ranunculus acris	B	CE	M	D	BCEMD	10	10	10	10	10	10	60
Ranunculus auricomus agg.	C	CE	G	D	CEGD	10	10	10	10	10	10	32.5
Ranunculus ficaria	D	CE	G	D	DCEGD	10	10	10	10	10	10	17.5
Ranunculus flammula	B	RA	R	D	BRARD	10	10	10	10	10	10	27.5
Ranunculus lingua	C	SC	M	F	CSCMF	R	10	V	10	10	10	90
Ranunculus repens	B	RA	M	D	BRAMD	10	10	10	10	10	10	30
Ranunculus sceleratus	B	RA	G	D	BRAGD	10	10	10	10	10	10	37.5
Rhinanthus angustifolius [s.l.]	A	SC	M	D	ASCMD	R	10	10	10	10	V	45
Rhinanthus minor	A	SC	M	D	ASCMD	10	R	10	10	10	10	30
Ribes nigrum	D		M	D	DMD	10	10	10	10	10	10	105
Ribes rubrum	D		M	D	DMD	10	10	10	10	10	10	220
Rorippa amphibia	B	CM	G	F	BCMGF	10	10	10	10	10	10	80
Rorippa palustris	A	CE	M	D	ACEMD	10	10	R	10	10	10	32.5
Rubus fruticosus agg.	D		M	D	DMD	10	10	10	10	10	10	100
Rubus idaeus	D		M	D	DMD	10	10	10	10	10	10	105
Rumex acetosa	B	CE	M	D	BCEMD	10	10	10	10	10	10	75
Rumex acetosella	A	O	M	D	AOMD	10	10	10	10	10	10	35
Rumex conglomeratus	A	CE	M	D	ACEMD	10	10	10	10	EN	10	75
Rumex crispus	A	RA	M	D	ARAMD	10	10	10	10	10	10	125
Rumex hydrolapathum	C	CM	G	F	CCMGF	10	10	R	10	10	10	125
Rumex obtusifolius	A	RA	M	D	ARAMD	10	10	10	10	10	10	115
Sagina nodosa	A	SC	G	D	ASCGD	V	VU	10	10	10	10	4.5
Sagina procumbens	A	RA	G	D	ARAGD	10	10	10	10	10	10	4.5
Salix aurita	D	F	R	D	DFRD	10	10	10	10	10	10	130
Salix cinerea	D	F	M	D	DFMD	10	10	10	10	10	10	400
Salix multinervis	D	F	M	D	DFMD	10	10	10	10	10	10	330
Salix pentandra	D	F	M	D	DFMD	10	10	10	10	10	10	675
Salix repens [s.l.]	A	SC	M	D	ASCMD	10	10	10	10	10	10	57.5
Sambucus nigra	D		M	D	DMD	10	10	10	10	10	10	450
Sanguisorba officinalis	A	SC	M	D	ASCMD	10	10	10	10	10	10	65
Saxifraga granulata	A	CE	M	D	ACEMD	10	10	10	10	10	10	32.5
Scheuchzeria palustris	A	SC	R	D	ASCRD	V	CR	10	10	10	V	15
Schoenoplectus lacustris	D	SC	G	F	DSCGF	10	10	10	10	10	10	212.5
Schoenoplectus tabernaemontani	D	SC	G	F	DSCGF	10	10	10	10	10	10	162.5
Scirpus sylvaticus	D	CE	M	D	DCEMD	10	10	10	10	10	10	57.5
Scutellaria galericulata	D	CM	G	D	DCMGD	10	10	10	10	10	10	30
Secale cereale	A	O	M	D	AOMD	10	10	10	10	10	10	125
Senecio aquaticus	A	CM	M	D	ACMMD	10	10	10	10	VU	10	75
Senecio vulgaris	A	O	M	D	AOMD	10	10	10	10	10	10	28.5

C Plant species list

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table	Red lists ^a						mid. Plant height in cm	
					Germany	Netherlands	Norway	Poland	Sweden	Great Britain		
<i>Setaria viridis</i>	A	O	M	D	AOMD	10	10	10	10	NT	10	51
<i>Silene dioica</i>	D	O	G	D	DOGD	10	10	10	10	10	10	60
<i>Sisymbrium officinale</i>	A	O	M	D	AOMD	10	10	10	10	10	10	55
<i>Sium latifolium</i>	C	CE	G	F	CCEGF	10	10	10	10	10	10	90
<i>Solanum dulcamara</i>	D		M	D	DMD	10	10	10	10	10	10	115
<i>Solanum nigrum</i>	A	O	G	D	AOGD	10	10	10	10	10	10	32.5
<i>Sonchus asper</i>	A	O	G	D	AOGD	10	10	10	10	10	10	45
<i>Sorbus aucuparia</i>	D		M	D	DMD	10	10	10	10	10	10	110
<i>Sparganium erectum</i>	D		G	F	DGF	10	10	10	10	10	10	65
<i>Sparganium minimum/natans</i>	D		R	F	DRF	V	10	10	10	10	10	55
<i>Spergularia arvensis</i>	A	O	M	D	AOMD	10	10	10	10	10	10	27.5
<i>Sphagnum angustifolium</i>	A	SC	R	D	ASCRD	10	10	10	10	10	10	6.5
<i>Sphagnum capillifolium</i>	A	SC	R	D	ASCRD	10	10	10	10	10	10	6.5
<i>Sphagnum cuspidatum</i>	A	SC	R	D	ASCRD	10	10	10	10	10	10	6.5
<i>Sphagnum fallax</i>	B	SC	R	D	BSCRD	10	10	10	10	10	10	6.5
<i>Sphagnum fimbriatum</i>	B	SC	R	D	BSCRD	10	10	10	10	10	10	6.5
<i>Sphagnum flexuosum</i>	A	SC	M	D	ASCMD	10	10	10	10	10	10	6.5
<i>Sphagnum palustre</i>	B	SC	R	D	BSCRD	10	10	10	10	10	10	6.5
<i>Sphagnum papillosum</i>	A	SC	R	D	ASCRD	10	10	10	10	10	10	6.5
<i>Sphagnum squarrosum</i>	B	SC	R	D	BSCRD	10	10	10	10	10	10	6.5
<i>Sphagnum subsecundum</i> agg.	A	SC	R	D	ASCRD	10	10	10	10	10	10	6.5
<i>Sphagnum teres</i>	B	SC	M	D	BSCMD	10	10	10	10	10	10	6.5
<i>Sphagnum warnstorffii</i>	D	SC	M	D	DSCMD	10	10	10	10	10	10	6.5
<i>Stachys palustris</i>	C	SC	M	D	CSCMD	10	10	10	10	10	10	55
<i>Stachys sylvatica</i>	D		G	D	DGD	10	10	10	10	10	10	75
<i>Stellaria glauca/palustris</i>	B	CM	R	D	BCMRD	R	10	DC	10	10	10	35
<i>Stellaria graminea</i>	A	CE	M	D	ACEMD	10	10	10	10	10	10	50
<i>Stellaria holostea</i>	D		M	D	DMD	10	10	10	10	10	10	32.5
<i>Stellaria media</i> agg.	D	RA	M	D	DRAMD	10	10	10	10	10	10	25
<i>Stellaria nemorum</i>	D		M	D	DMD	10	10	10	10	10	10	45
<i>Stellaria uliginosa</i>	B	RA	R	D	BRARD	10	10	10	10	10	10	25
<i>Succisa pratensis</i>	A	SC	M	D	ASCMD	10	R	10	10	10	10	60
<i>Symphytum officinale</i>			M	D	MD	10	10	10	10	10	10	65
<i>Tanacetum vulgare</i>	A	O	G	D	AOGD	10	10	10	10	10	10	90
<i>Taraxacum officinale</i> agg.	B	RA	M	D	BRAMD	10	10	10	10	10	10	25
<i>Thalictrum flavum</i>	C	SC	G	D	CSCGD	10	10	10	10	10	10	67.5
<i>Thelypteris palustris</i>	D	SC	M	D	DSCMD	R	10	DC	10	10	10	57.5
<i>Thlaspi arvense</i>	A	O	G	D	AOGD	10	10	10	10	10	10	32.5
<i>Trichophorum cespitosum</i>	D		R	D	DRD	10	10	10	10	10	10	5
<i>Trianthis europaea</i>	D	F	R	D	DFRD	10	10	10	10	10	10	12.5
<i>Trifolium dubium</i>	A	CE	M	D	ACEMD	10	10	10	10	10	10	17.5
<i>Trifolium pratense</i>	A	CM	M	D	ACMMD	10	10	10	10	10	10	32.5
<i>Trifolium repens</i>	A	RA	M	D	ARAMD	10	10	10	10	10	10	15
<i>Triglochin maritimum</i>	A	CE	M	D	ACEMD	R	10	10	10	10	10	32.5
<i>Triglochin palustre</i>	A	CM	M	D	ACMMD	R	10	10	10	10	10	37.5
<i>Tripleurospermum inodorum</i>	A	O	M	D	AOMD	10	10	10	10	10	10	30
<i>Triticum aestivum</i>	A	O	M	D	AOMD	10	10	10	10	10	10	115
<i>Typha angustifolia</i>	D		M	F	DMF	10	10	10	10	10	10	200
<i>Typha latifolia</i>	D		M	F	DMF	10	10	10	10	10	10	175
<i>Urtica dioica</i>	D	O	M	D	DOMD	10	10	10	10	10	10	165
<i>Urtica urens</i>	A	O	M	D	AOMD	10	10	10	10	10	10	37.5
<i>Utricularia intermedia</i>			G	F	GF	V	VU	10	10	10	10	30
<i>Utricularia vulgaris</i>			M	F	MF	R	10	10	10	10	10	115
<i>Vaccinium myrtillus</i>			R	D	RD	10	10	10	10	10	10	62.5
<i>Vaccinium oxycoccos</i>			R	D	RD	R	VU	10	10	10	10	62.5

(continuation of the plant species list)

Species name	Abandonment category	Intensification category	Water source	Water table		Red lists ^a						mid. Plant height in cm
						Germany	Netherlands	Norway	Poland	Sweden	Great Britain	
Valeriana dioica	B	SC	M	D	BSCMD	10	VU	Ex	10	10	10	90
Valeriana officinalis agg.	D	CE	G	D	DCEGD	10	10	10	10	10	10	90
Veronica arvensis		O	M	D	OMD	10	10	10	10	10	10	16
Veronica beccabunga	D	CE	G	F	DCEGF	10	10	10	10	10	10	37.5
Veronica chamaedrys	A	CE	M	D	ACEMD	10	10	10	10	10	10	25
Veronica hederifolia	A	O	G	D	AOGD	10	10	10	10	10	10	18.5
Veronica longifolia			G	D	GD	R	10	10	10	10	10	90
Veronica persica	A	O	G	D	AOGD	10	10	10	10	10	10	22.5
Veronica scutellata	A	CM	R	D	ACMRD	10	10	10	10	10	10	18.5
Veronica serpyllifolia	A	CE	M	D	ACEMD	10	10	10	10	10	10	15
Viburnum opulus	D	F	G	D	DFGD	10	10	10	10	10	10	22.5
Vicia cracca	B	CM	M	D	BCMMD	10	10	10	10	10	10	11.5
Vicia hirsuta	A	O	M	D	AOMD	10	10	10	10	10	10	4.5
Vicia sativa	A	O	M	D	AOMD	10	10	10	10	10	10	6.0
Viola arvensis	A	O	M	D	AOMD	10	10	10	10	10	10	22.5
Viola palustris	B	SC	M	D	BSCMD	10	10	10	10	10	10	10
Viola persicifolia			M	D	MD	V	EN	V	VU	10	EN	12.5
Viola riviniana	D	F	M	D	DFMD	10	10	10	10	10	10	20
Viola tricolor	A	O	M	D	AOMD	10	10	10	10	10	10	22.5

^aShortcuts of red lists (translation into number):

Germany, Norway:

Ex = extinct (0), E = endangered (1), V = vulnerable (2), R = rare (3), GR = rare (4), DC = declining, care demanded (4), I = endangerment suspected (4), 10 = not conservation dependent (-)

IUCN, Sweden, The Netherlands, Poland, Great Britain:

RE = regionally extinct (0), EX = extinct (0), CR = critically endangered (1), EN = endangered (2), VU = vulnerable (3), NT = near threatened (4), R = rare (4), 10 = not conservation dependent (-)

D Questionnaire for chapter 6.3

Questionnaire: Modelling long-term changes of ecosystem functions of EUROPEAT peatland sites with PMDSS (Astrid Knieß, Michael Trepel)

Author(s):

Country:

Site name:

Site description: Describe your site with 2 - 3 sentences.

Objectives: Describe the objectives of the model run. Formulate a question, why you are choosing this model run in relation to the problems associated with peatland use in your region.

Business as usual scenario

Run the business as usual scenario for your site.

Input data: Copy the input data table from the worksheet *Input_Par* and insert here. Indicate the data source and quality (measurements, expert judgment, guess).

Input_TimeSeries: If you use the worksheet *Input_TimeSeries*, indicate the input you have done there (eg. mean summer water table = 50 cm below surface every 15th year).

Input_Tab: If you have done adjustments in worksheet *Input_Tab* indicate them.

Mod_Adj: If you have used own equations in *Mod_Adj*, give a short description.

Land use and water management scenarios

Select scenarios for change in land use and/or water management. Give a short description of the scenarios. Make a table with the changed input parameters.

Results

Describe selected results from the model runs for business as usual and other scenarios to answer your questions. Insert selected graphs from the worksheets *Res_TimeSeries* and *Res_Amoeba*.

Validation

Describe if the results are plausible. Compare results with measurements, literature values and/or expert knowledge (use tables).

Feedback

Advantages of PMDSS: Describe the advantages.

Disadvantages of PMDSS: Describe the disadvantages.

Suggestions: Do you have suggestions, what should further be implemented into PMDSS?

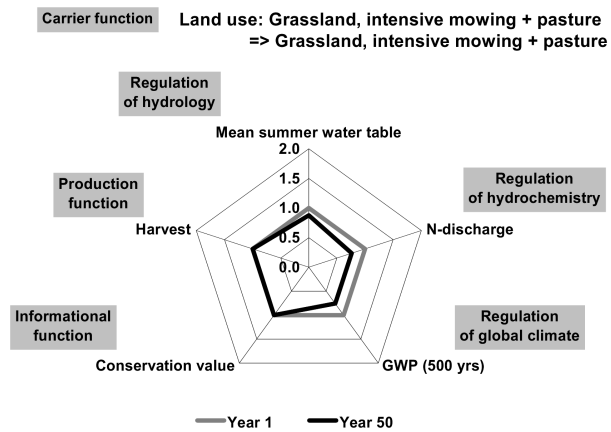
Please answer some questions about PMDSS and do one cross for each question.

	Quite clear what was going on	Moderately clear	Just coping	Have not got the foggiest notion
Did you fully understand what this model was about?				
Regarding the parameter modifications				
How confident do you feel about interpreting the results you got?				

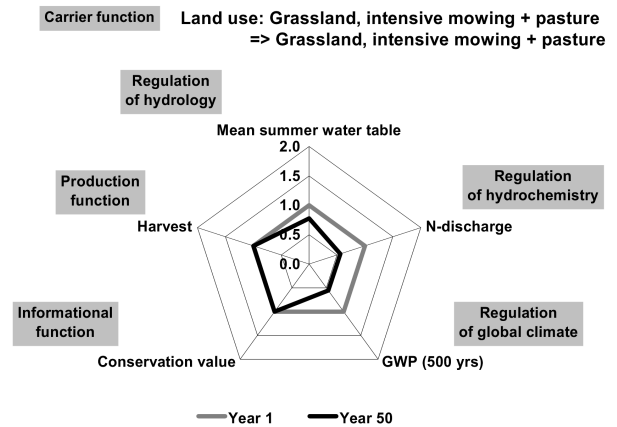
References

Provide references.

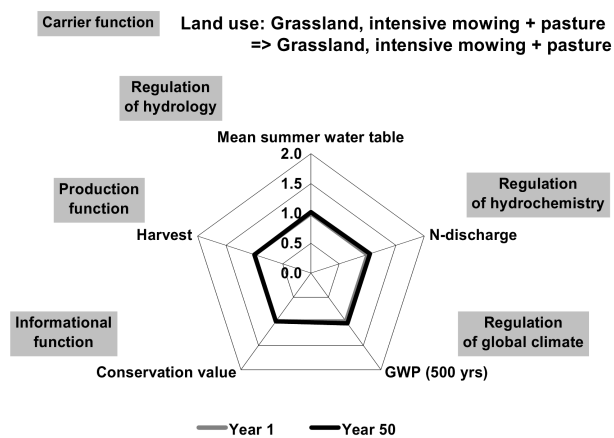
E Result diagrams of chapter 6.3



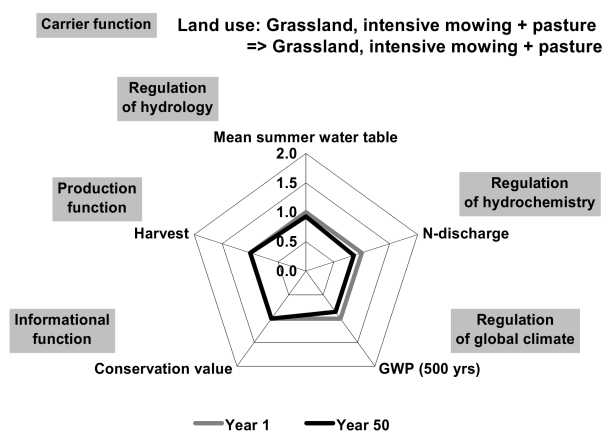
(a) Business as usual



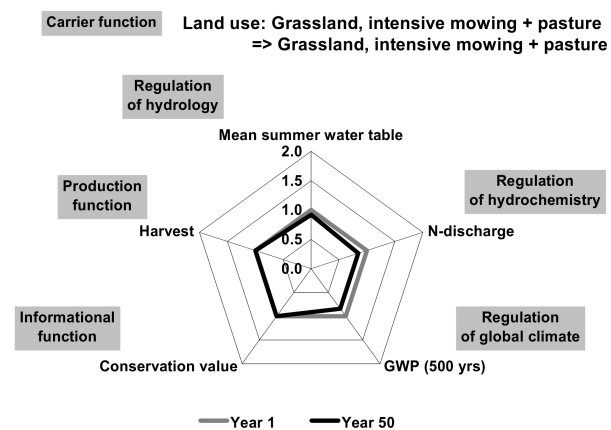
(b) Drain level 30 cm



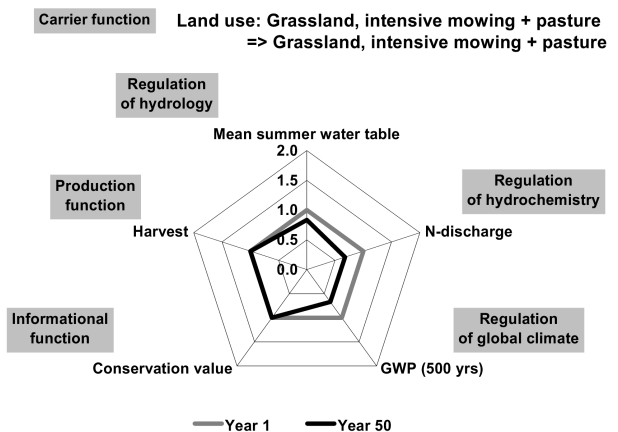
(c) Dry climate



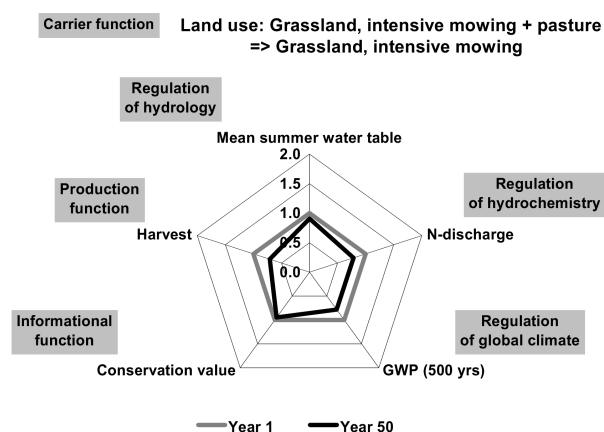
(d) Infiltration drains (dry climate)



(e) Grading



(f) Sprinkling



(g) Maize

Figure E.1: Results of land use and water management scenarios for the **Netherlands, Zegveld 03**. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line), the black lines show the relative changes of the indicators 50 years after the initial state, whereas the maximum was set to 2.6.

E Result diagrams of chapter 6.3

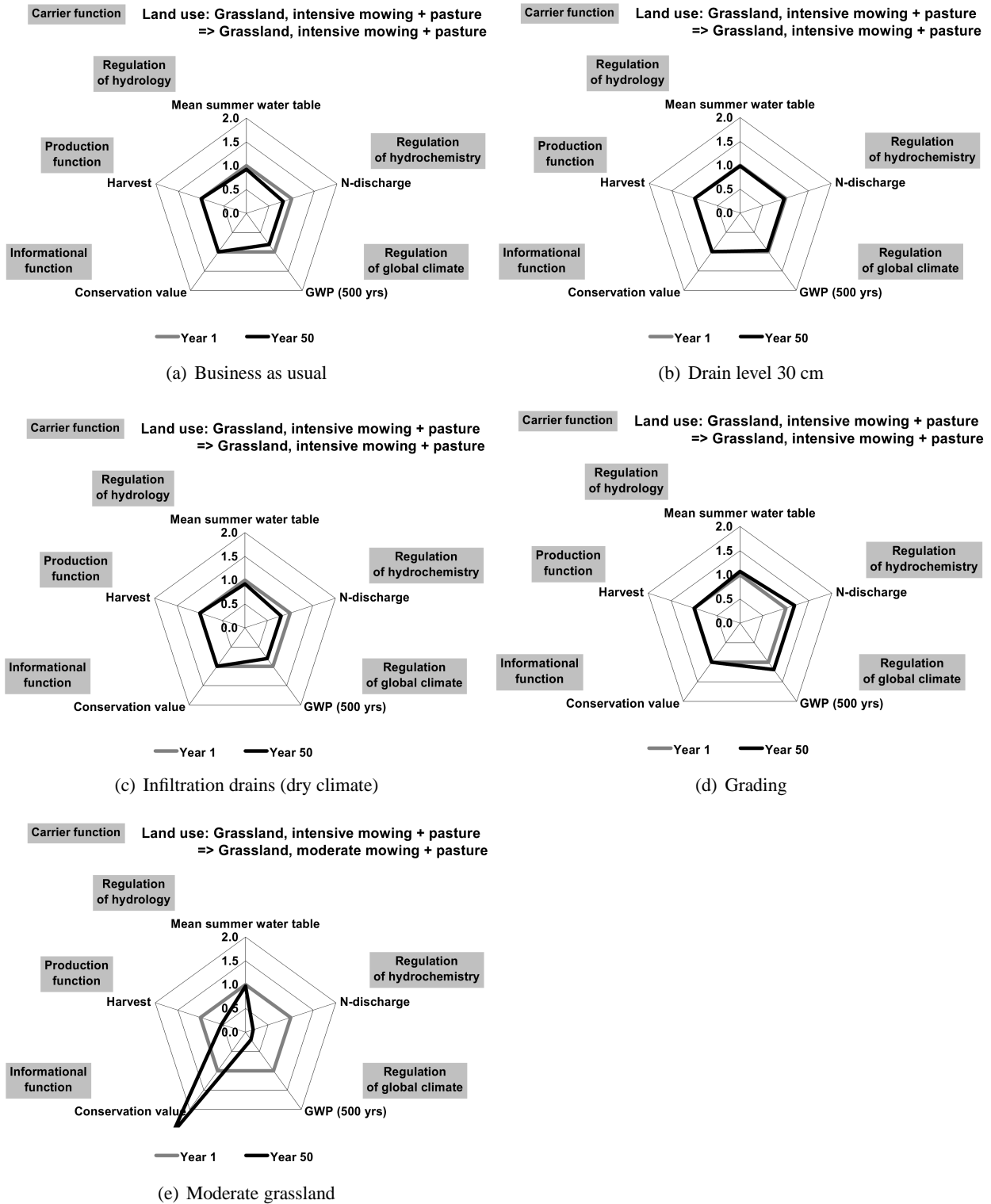


Figure E.2: Results of land use and water management scenarios for the **Netherlands, Zegveld 13**. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line), the black lines show the relative changes of the indicators 50 years after the initial state, whereas the maximum was set to 2.6.

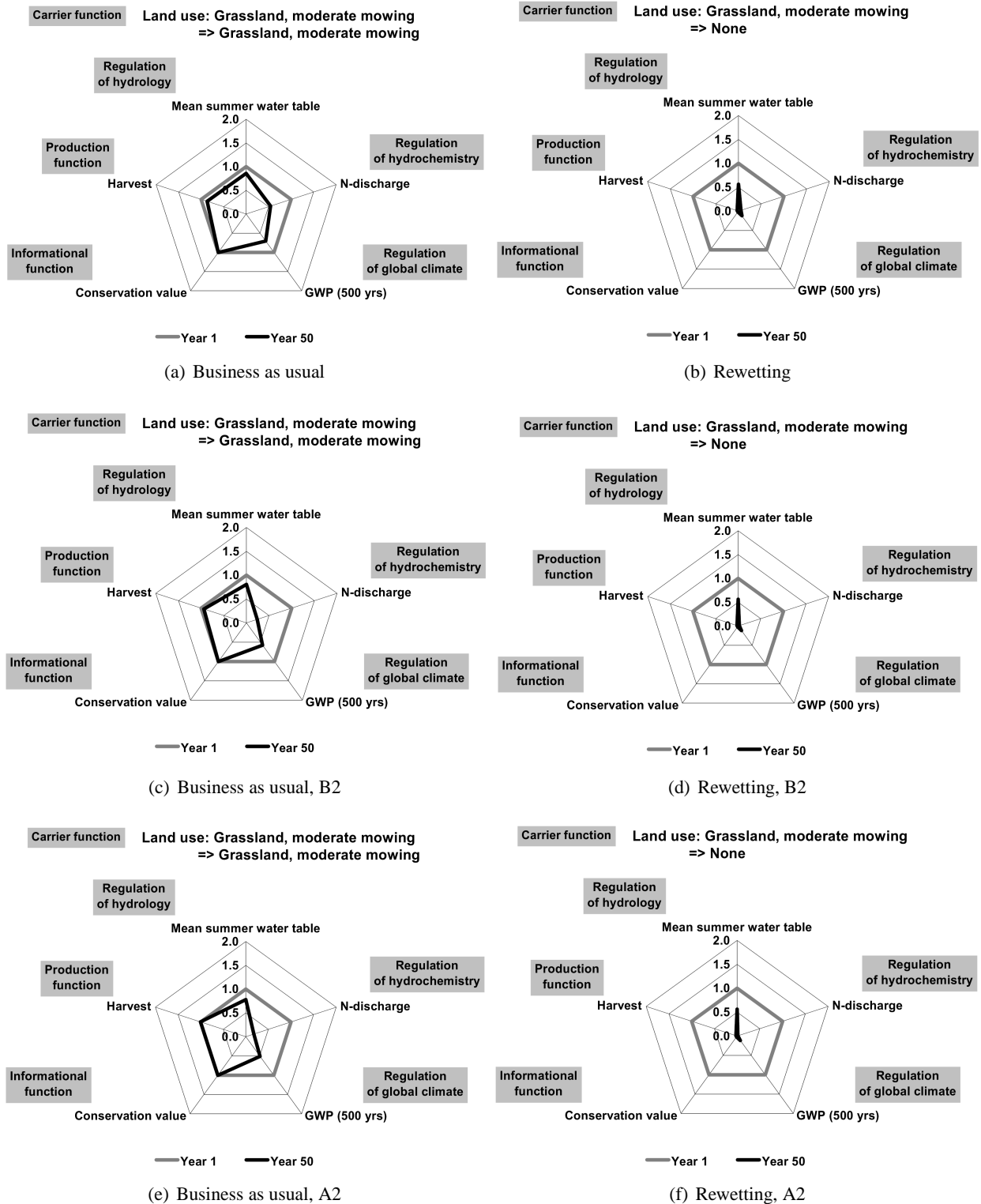


Figure E.3: Results of land use and water management scenarios for **Sweden**. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line), the black lines show the relative changes of the indicators 50 years after the initial state, whereas the maximum was set to 2.6.

E Result diagrams of chapter 6.3

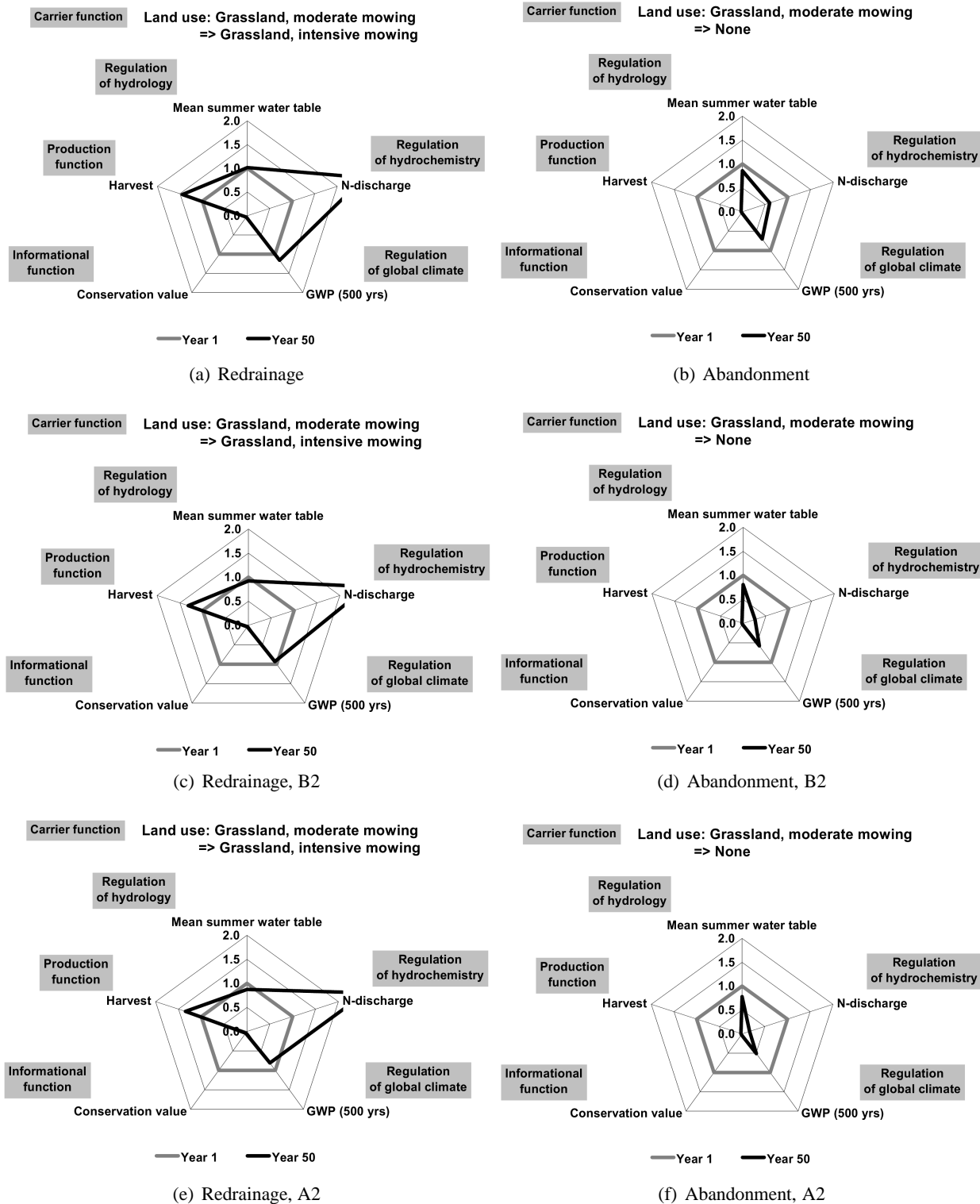


Figure E.4: Results of land use and water management scenarios for **Sweden**. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line), the black lines show the relative changes of the indicators 50 years after the initial state, whereas the maximum was set to 2.6.

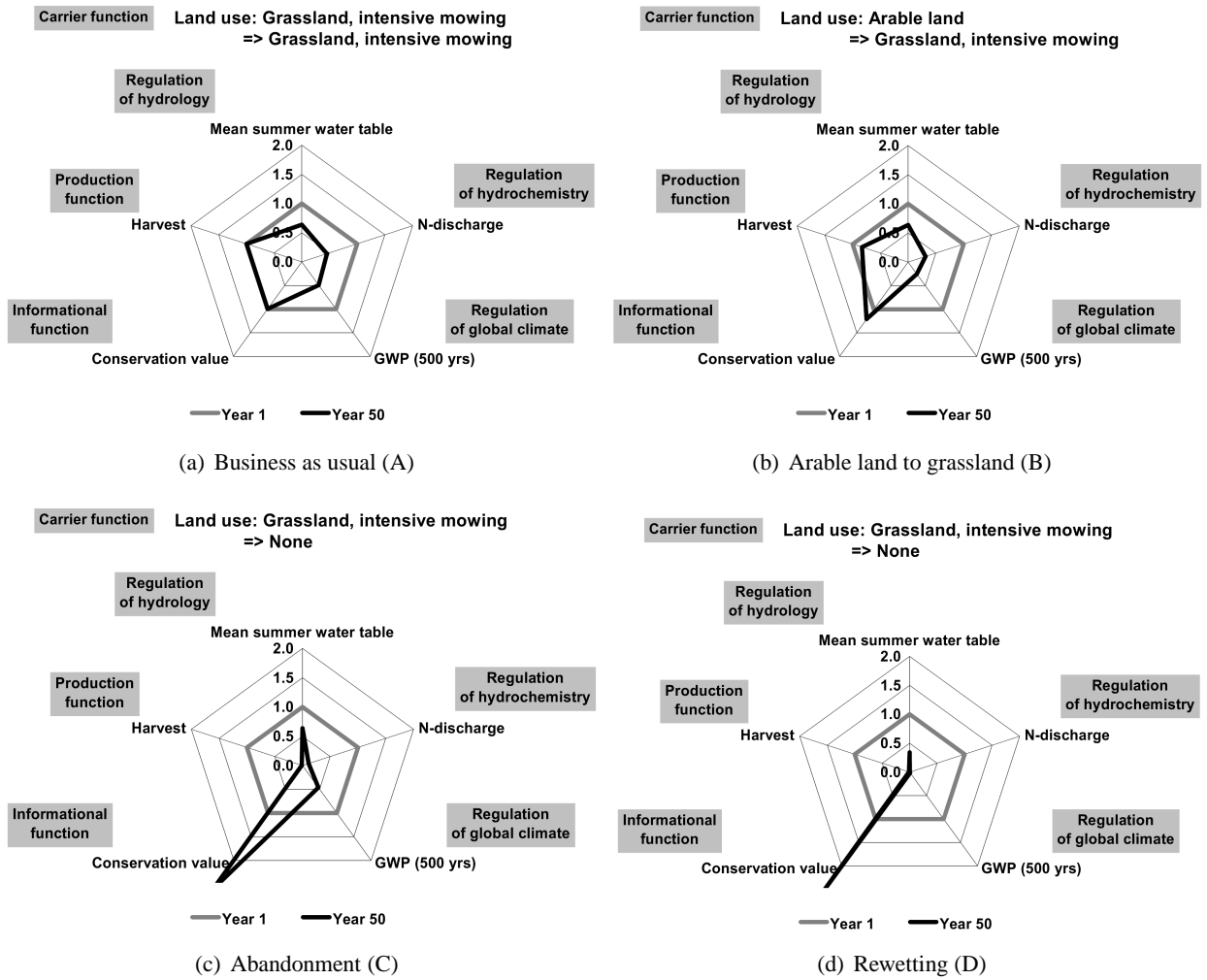


Figure E.5: Results of land use and water management scenarios for **Norway**. PMDSS output as amoeba diagram: initial values of indicators were set to 1 (grey line), the black lines show the relative changes of the indicators 50 years after the initial state, whereas the maximum was set to 2.6.

Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertation selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel von mir eingesetzt worden sind. Des weiteren versichere ich, dass die vorliegende Dissertation weder ganz noch zum Teil bei einer anderen Stelle im Rahmen eines Prüfungsverfahrens vorgelegen hat.

Teile der Arbeit wurden veröffentlicht beziehungsweise zur Veröffentlichung eingereicht:

- Knieß, A. & M. Trepel (2007): A decision support system to predict long-term changes in peatland functions. In: T. Okruszko, E. Maltby, J. Szatyłowicz, D. Świątek & W. Kotowski (eds.): Wetlands: Monitoring, Modelling and Management, pp. 255-262. Taylor & Francis/Balkema, London.
- Knieß, A., M. Trepel, B. Holsten & W. Kluge (submitted): Prediction of long-term changes in ecosystem functions of a peatland site with the semi-quantitative decision support system PMDSS. (Submitted to a special issue of the EUROPEAT project in Geoderma)

Kiel, 24.10.2007