Modelling the Implications of Climate Change for European Freshwater Wetland distributions

A Review of Knowledge and Gaps

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Abstract. This review contributes to a project promoted by the cluster of excellence "Integrated Climate System Analysis and Prediction (CliSAP)" to evaluate the preservation potentials of freshwater wetlands in Europe under consideration of climate change. In Europe wetlands have been drained and converted for centuries. The remaining wetlands are fragmented and often in a degraded state. During the last years efforts have been made to restore and preserve wetlands for various purposes, because wetlands provide crucial services and functions. They affect the carbon, water, and nitrogen cycles, serve as habitat for many plant and animal species, and act both as sink and source of greenhouse gases. In this sense, wetlands, its functions, and spatial extension may also be of significance in global and regional climate modeling. A fully coupled wetland-climate model under consideration of land use has not yet been developed; and within earth system models, wetlands are included as static shape with fixed boundaries. Wetlands have also received little attention in large-scale economic models of land use. But with relatively high European political ambitions for climate change mitigation, biodiversity protection, energy, water, food, and civil security, the question arises how to optimally govern wetlands in order to maximize market and non-market benefits. Qualitative and quantitative data on wetland ecosystems, its functions and services are required as base input for such model approaches. But often these studies are hindered by a lack of knowledge on wetland ecosystem functions, processes, as well as its spatial and temporal distribution under changing conditions. This paper summarizes existing knowledge on European freshwater wetlands under changing climatic conditions and discusses research gaps needed to be filled. The paper further compares the results with research undertaken globally by indicating uncertainties and variations.

Keywords: Coupled Modeling, Systematic Wetland Conservation, Wetland Resource Management

1. Introduction

Wetlands are the transitional areas between aquatic and terrestrial environments. They vary in soil, topography, climate, hydrology, water chemistry, vegetation, and often also because of human disturbance (Pott & Remy, 2000). The main focus of this study is European inland freshwater wetlands. In Europe, inland wetlands are most common on floodplains along rivers and streams, along the margins of lakes and ponds, on slopes associated with springs, as well as in low-lying areas or depressions where the groundwater intercepts the soil surface or where precipitation sufficiently saturates the soil. According to the Ramsar Convention on Wetlands (Ramsar, Iran, 1971, Articles 1.1 and 2.1 of the convention), inland wetlands also include shrub- or tree-dominated swamps, as well as marshes and wet meadows dominated by herbaceous plants, which are usually manmade. Many of these wetlands are seasonal and may be wet only periodically. The quantity of water present and the timing of its presence partly determine the functions of a wetland and its role in the environment (Mulamoottil et al., 1996).

The majority of European wetlands have for centuries been subject to anthropogenic modification, principally through drainage and conversion to other land uses. Indeed, it has been estimated that more than 70% of all European wetlands existing at the beginning of the 20th century have since been lost to urbanization, peat extraction, or agriculture (Joosten & Clarke, 2002), and those remaining are fragmented and often in a degraded state. This has culminated in the situation we face today, in which wetlands are recognized as one of the most threatened ecosystems in Europe and throughout the rest of the world (Millennium Ecosystem Assessment, 2005).

Recent efforts have aimed to restore and preserve European wetlands, driven mainly by the recognition that they provide crucial services and functions, but also because of their high cultural value (European Commission, 2010). Wetlands affect, among others, the carbon, water, and nitrogen cycles, and serve as habitat for many plant and animal species. The latest IPCC Report states that climate change may have significant impacts on the world's wetland resources (Parry et al., 2007; Bates et al., 2008), including a decline in functioning wetland areas within most ecoregions and a shift in the geographic location of certain types of wetlands (Erwin, 2009). At the same time, some studies have also shown that wetlands might play a significant role in the global greenhouse gas budget (Drösler et al., 2008). In this sense, wetlands, their functions, and spatial extension are of great significance in terms of global and regional nature conservation and land use planning, but also in climate modeling.

The European Union has set out relatively high political ambitions for climate change mitigation and biodiversity protection, as well as for energy, water, food, and civil security (cf. European Commission, 2006 and 2010). Wilby et al. (2010) list those European research programs that are addressing aspects of climate change and freshwater ecosystem management, and within this context the question arises as to how one governs wetlands optimally, against the backdrop of potential climate change effects, in order to maximize market and non-market benefits. In principal, integrated models that consider land use, the distribution of ecosystems, as well as hydrology and climate, are most suitable for solving such large-scale problems. However, all of these models require qualitative and quantitative data on wetland ecosystems, their functions and services, as well as their resilience to changing climates or hydro-periods as their base inputs.

The aims of this study are: (i) to give an overview of existing data on freshwater wetlands in Europe; (ii) to summarize the state of the art in European wetland distribution modeling; and (iii) to review the scientific knowledge about climate-change-driven implications for wetland distributions in Europe. The main discussion point is the feasibility of integrating the compiled knowledge into regional climate and land use models. Contingent research gaps in this context will furthermore be highlighted.

2. Materials and Methods

To successfully integrate wetlands into land use and nature conservation planning on a European scale, we need geospatial information in three key areas. First, information on the actual distribution of existing wetlands and their characteristics, such as size, land use, human impacts, and conservation status is crucial. Second, we need to identify replacement areas that are potentially suitable for wetland restoration or evasion, and this should be done according to physical and natural conditions, as well as in relation to strategic and economic factors. And third, the attributes and performance of wetlands under changing conditions in hydrology and climate need to be estimated. This also includes knowledge of the relationships between catchments and their wetlands. To evaluate the available information, we performed a literature search on the following topics using ScienceDirect, ISI Web of Knowledge, and Google Scholar:

a. wetland inventories and existing data on wetlands in the European landscape
b. wetland distributions in models and models of wetland distributions
c. ecosystem resilience and the effect of wetlands under climate change

For a particular study to be included in the review, it had to meet certain criteria; namely, it must have taken place in Europe, and it must have had a spatial component regarding wetland distribution. Only peer reviewed and published studies were selected, and relevant journal articles were found in the databases using keyword searches in the three topic areas, as well as through scanning the reference lists of these articles for further literature. Using the above criteria, searches for studies covering the keyword *wetland* were carried out, as well as further searches for papers relating to the following wetland type names: *alluvial forest, bog, fen, floodplain, forested swamp, lake, marsh, moor, peatland, mire, reed, riverine forest, shallow pond, swamp, wet forest, wet grassland,* and *wet heath*. Studies conducted outside of Europe were also taken into account for comparison purposes, as well as for a more adequate interpretation of knowledge gaps.

3. Results

3.1. Spatial Data: Wetland Inventories and Wetlands in the European Landscape

Current climate and land use models are generally conducted on global to continental or regional scales (cf. table 2). Owing to their vast coverage areas, these models rely mainly on external data rather than field measurements. Knowledge of position, size and functions of wetlands in the landscape represent important prerequisites for the programming of coherent models aimed at showing potential ecosystem changes. In this respect, data integrity is of special significance in order to minimize uncertainties and avoid inaccuracies. To date, statistics and data from national or regional wetland inventories have been utilized for such models, and most recently, cartographic data have also been developed from remote sensing and earth observation techniques (e.g. Prigent et al., 2007). This section provides an overview of existing data on European freshwater wetlands.

3.1.1. Wetland Inventories

The identification of wetlands and their resources is important for policy making. Wetland inventories serve, for example, as tools for the identification of Ramsar sites of international importance (Ramsar Bureau). Furthermore, their quantification and spatial delineation is important for status and trend analyses of wetland resources, for selecting wetlands suitable for restoration, as well as for risk and vulnerability assessments (MacKay et al., 2009). On behalf of the Ramsar Convention, numerous national and regional wetland inventories have been enforced. The *Global Review of Wetland Resources and Priorities for Wetland Inventory – GroWI* (Finlayson & Spiers, 1999) reviews the extent and status of national wetland inventories. The achievements and limitations of global wetland inventories have also been assessed and reported as part of the Millennium Ecosystem Assessment (2005). As an update and extension of GroWI, Nivet & Frazier (2004) published a review of Pan-European Wetland Inventory (PEWI) information, which was based on national datasets and described their status and limitations. Since 1991, the Mediterranean Wetlands Initiative of the Ramsar Convention on Wetlands (MedWet) has collected information on Mediterranean wetlands in a comprehensive database (Costa et al., 1996). Analyses of the wetland inventory information show that these are inappropriate as a base for consistent spatial distribution modeling of wetlands. PEWI revealed that only 13% of European wetland inventory material was available as part of a GIS or in a GIS-compatible format (Nivet & Frazier, 2004). The existing reviews of PEWI and MedWet clearly demonstrate that existing data on European wetlands are neither exhaustive nor utilize standardized wetland definitions or consistent methodologies, which hampers delineation and international comparisons of the individual country estimates (Tiner, 2009). Despite improved coordination and integrative inventory regulations, and notwithstanding advancements in earth observation applications (Keramitsoglou et al., 2005; Fernandez-Prieto et al., 2006; Fitoka & Keramitsoglou, 2008; Melendez-Pastor et al., 2010), exact spatial information is still absent for many areas of Europe (van Diggelen et al., 2006). Even the most comprehensive wetland inventory information, PEWI, can only be seen as an estimate of described wetland cover, and not as true wetland cover. According to Nivet & Frazier (2004), the reported data underestimate the extent of wetland sites. Furthermore, it is difficult to assess the degree of completeness of individual inventories; plus, estimates of the rate of wetland loss and degradation in Europe are incomplete or based on unsubstantiated assertions (Moser et al., 1996; Finlayson et al., 2005; Rebelo et al., 2009). Most recent inventories specify the coordinates and extent of the identified wetlands more precisely, as well as ascertain details of the state of the wetland and its physical (especially hydrological) and biological functions. These data are of great importance for the development of general statements required in models, but so far the spatial (and internal) consistency of the combined datasets remains rather limited.

3.1.2. Earth Observation and Wetland Distribution

Earth observation technology plays an important role in the provision of wetland geo-information (MacKay et al., 2009). It simplifies the identification and mapping of wetlands at various scales. Several initiatives have started to use earth observation to provide better information about wetland distribution, extent, functions and the interactions between wetlands and agriculture (Fernandez-Prieto et al., 2006; Davidson & Finlayson, 2007; Rosenqvist et al., 2007). The Millennium Ecosystem Assessment (2005) promotes the need to build a global assessment and monitoring capability based upon earth observation applications. The GlobWetland project (http://www.globwetland.org) was launched in 2003 on behalf of the European Space Agency (ESA) and the Ramsar Convention Secretariat. Its aims are to develop a coherent and globally comparable dataset of geo-information on wetlands by using earth observation techniques. A detailed description of the GlobWetland project can be found in Jones et al. (2009). Within the framework of the MedWet initiative, Fitoka & Keramitsoglou (2008) describe inventory, assessment, and monitoring guidelines for Mediterranean wetlands. Besides inventory assessments, earth observation techniques have been used to locate the seasonal and episodic inundation of forested and non-forested ecosystems more easily (e.g. Rosenqvist et al., 2007), to evaluate status, trends, and changes in wetland ecosystems (Kleinod et al., 2005; Milzow et al., 2010), and to derive information on wetland functions (Cai & Ji, 2009). In this respect, not only satellite data, but also aerial photographs, are a widely used data source (Murphy et al., 2007; Aber et al., 2010). So far, these approaches have resulted in multiple-scale case studies, where improved wetland-specific methods are tested for newly available and advanced remote sensing data (Fernandez-Prieto et al., 2006; Davidson & Finlayson, 2007; Rosenqvist et al., 2007; Alexandridis et al., 2009; Bartsch et al., 2009; Rebelo et al., 2009). However, Pan-European comprehensive spatial wetland distribution data based on remote sensing initiatives are still lacking, and in this respect the GEOSS (Global Earth Observation System of Systems) and EuroGEOSS (A European Approach to GEOSS) initiatives promise to deliver improved data availability (cf. GEO Secretariat, 2009). Niu et al. (2009) have shown that such large-scale products are possible in developing spatially consistent wetland information for China from Landsat ETM+ data.

3.1.3. Comprehensive Spatial Data on European Wetland Distribution

Wetland distribution at a global scale has been mapped by Matthews & Fung (1987), Aselmann & Crutzen (1989), Stillwell-Soller et al. (1995), Darras et al. (1999), Global Land Cover (European Commission, 2003), Lehner & Döll (2004), and Prigent et al. (2007). Mitra et al. (2005) compared the outputs of several global wetland databases. Owing to the global perspectives of these initiatives, spatial resolutions tend to be coarse, and wetlands are seldom differentiated in detail, making the use of these data for wetland modeling studies at the European scale inappropriate. Few datasets can be used to obtain information about European wetland distribution. For example, the Ramsar list is not fully representative of European wetlands because it only includes wetlands of special interest. The EUNIS (European Nature Information System) database, with its distinction of over 2600 terrestrial habitat classes at the fourth level (Moss & Davies, 2002 a, b), is very detailed in the information it contains about wetland habitats in Europe; however, the spatial data are not complete and use mainly aggregated CORINE Land Cover data of ten major habitat types according to the EUNIS habitat classification.

The CORINE land cover database (EEA, 2000) is the most detailed database covering the European Union. One disadvantage for ecosystem studies is the heterogeneity of the classes determined by functional land use and not by land cover itself. While the Ramsar database or CORINE biotopes data identify both permanent and seasonal wetlands, CORINE identifies permanent wetlands only. A digital map of potential natural vegetation in Europe produced by Bohn & Neuhäusel (2003) shows the potential distribution of wetland vegetation types across Europe. However, as this does not take human influences into account, it is only suitable for modeling future changes. The European Soil Database (European Commission, 2004) is also only conditionally suitable, limited to detecting wetlands through the identification of areas covered by wet soils. The difficulty is that the databases described above do not concentrate on wetlands alone, but instead cover the whole range of land cover and ecosystem types. Thus, forested and non-peat wetland areas are often included in other ecosystem classes. The GIS-based Spatial Wetland Distribution Model (SWEDI) (Schleupner, 2010) has been developed to overcome these problems. SWEDI is an extraction tool that denotes wetland allocations in Europe. It compiles spatial data describing the present distribution of wetlands and uses rule-based statements of spatially explicit information on physical and land cover parameters. SWEDI distinguishes between existing wetlands and those sites that might be suitable for wetland restoration and evasion but are currently under intensive human land use. Comprehensive statements about the state of wetland ecosystems are missing in all of the datasets described above.

3.1.4. On Estimations of the overall Extent of Wetlands in Europe

Regional and national wetland inventories are based on the aggregation of local information. Not surprisingly, estimations on the overall extent of wetlands in Europe are controversial due to the poor availability of data. Lehner & Döll (2004) stated a European wetland area of 26 million hectares, for example, whereas PEWI (Nivet & Frazier, 2004) has provided an estimate of 266 million hectares. Such differences arise because of differences in wetland delineation and definition, but also because of diverse regional demarcation. Therefore, comparisons such as the one above cannot be drawn in order to make statements about the accuracy of these data.

Table 1 illustrates examples of inconsistencies in wetland extent between different datasets within the borders of Germany. As wetland data are not collected at a federal level, no summaries of data on wetlands are available in Germany and the real wetland extent is hard to estimate. Additionally, there are regional variations in terms of quality and quantity of the wetland data within the country itself (German Ramsar National Report, 1998).

Table 1. Estimations of wetland areas in Germany from various sources

Source	wetland area in ha	wetland types included	comments
PEWI (Nivet & Frazier, 2004)	785,200 641,400	inland waters, mires	based more on national statistics rather than spatial data
Schultlink & Van Vliet (1997) German Ramsar National Report (1998)	2,107,483	fens, wet pastures, wet woodlands, water courses, lakes, reservoirs, dredging pools, open mining lakes, ponds and coastal areas up to a depth of 6 meters at low tide	
SWEDI (Schleupner, 2010)	133,383 448,462 11,345	peatland, wet forest, natural wet grassland (reeds, sedges)	
CORINE LC 2006 (EEA, 2000)	57,151 53,682 90,543	moors and heathland inland marshes peat bogs	
GLWD (Lehner & Döll, 2004)	328,472 40,556 278	lake river bog, fen, mire	rough global scale database
Global Land Cover Database (European Commission, 2003)	53,400 338,800	regularly flooded shrub and/or herbaceous cover water bodies	
Ramsar sites (2008)	296,414	inland wetlands including open waters	site area, not necessarily wetland area wetlands of special interest only
Irish Peatland Conservation Council (1998) Joosten & Clarke (2002)	1,300,000	peatland	
European Soil Database (European Commission, 2004)	8,446,300	wet or peaty soils	irrespective of actual land use

3.2. Wetland Distributions in Models and Models of Wetland Distributions

3.2.1. Wetland Distributions in Models

The vast majority of recent models that include wetlands treat them as static shapes with fixed boundaries (see table 2), thereby neglecting the fact that the area of a wetland may alter even with subtle changes in hydrology. A fully coupled wetland–climate model under consideration of land use has not yet been developed. Wetlands have also received little attention in large-scale economic models of land use. Table 2 shows examples of wetland base data for several integrated dynamic modeling approaches of the earth system.

Table 2. The inclusion and omission of wetlands in global- and European-scale models

base (wetland) data	model scope	reference	model type	comments
mapped wetlands	**global**			
Cogley (2003); Darras et al. (1999)	CLM4 (Community Land Model)	Oleson et al. (2010)	land surface model	land units: glacier, lake, wetland, urban, vegetated (wetlands = non-vegetated, no soil, constant)
↓	NCAR LSM (Land Surface Model)	Bonan et al. (2002)	land surface model	same as CLM4
Lehner & Döll (2004)	WaterGAP	Alcamo & Henrichs (2002)	water budget model	
Matthews & Fung (1987)	IGSM (Integrated Global System Model)	Solokov et al. (2005)	integrated model	zonal vegetation integrate cited wetland data, but wetlands are set constant
excluding wetlands	**global**			
BIOME Model, Plant functional types (PFT) (cf. Prentice et al., 1992)	GUMBO (Global Unified Metamodel of the Biosphere)	Boumans et al. (2002)	vegetation model	11 biomes globally aggregated, focusing on ecosystem goods and services
↓	Hybrid (Process-based, Terrestrial Biosphere Model of Ecosystem Dynamics)	Friend et al. (1997)	dynamic global vegetation model	8 PFT, preindustrial vegetation, no wetlands
↓	IBIS (Integrated Biosphere Simulator)	Kucharik et al. (2006)	dynamic global vegetation model	terrestrial ecosystems, no wetlands
↓	LPJmL (Lund-Potsdam-Jena dynamic global vegetation model including managed land)	Bondeau et al. (2007)	dynamic global vegetation model	10 PFT, no wetlands

↓	MC1	Bachelet et al. (2001)	terrestrial ecosystem model	21 vegetation classes, no wetlands
↓	SDGVM (Sheffield Dynamic Global Vegetation Model)	Woodward et al. (1998)	dynamic global vegetation model	vegetation dynamics in all climatic zones, no wetlands
↓	TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics)	Cox (2001)	dynamic global vegetation model	5 PFT, no wetlands
↓	VECODE (Vegetation Continuous Description Model)	Brovkin et al. (1997)	dynamic global vegetation model	potential vegetation, dynamics of grassland and forest, no wetlands
Global Land Cover (GLC) (European Commission, 2003)	GLOBIO3 (Global Methodology for Mapping Human Impacts on the Biosphere)	Alkemade et al. (2009)	biodiversity model	aggregated GLC, no wetlands, water bodies excluded
↓	IMAGE (Integrated Model to Assess the Global Environment)	Bouwman et al. (2006), Van Vuuren et al. (2006)	integrated model	no wetlands, water bodies excluded
mapped wetlands	**Europe**			
CORINE land cover, (EEA, 2000)	ATEAM (Advanced Terrestrial Ecosystem Analysis and Modeling)	Metzger et al. (2008)	terrestrial ecosystem model	regional assessments to the vulnerability of ecosystem services Europe (EU15 + Norway and Switzerland; 10' by 10' grid)
↓	MIRABEL (Models for Integrated Review and Assessment of Biodiversity in European Landscapes)	Petit et al. (2001)	biodiversity model	Europe (28 countries)
SWEDI (Spatial wetland Distribution model (Schleupner, 2010)	EUFASOM (European Forest and Agricultural Sector Optimization Model)	Schleupner & Schneider (2010)	mathematical optimization model	competing land utilization demands EU 27
↓	HABITAT	Jantke & Schleupner (2010)	systematic conservation planning model for wetland biodiversity	EU 27
census data	**Europe**			
national statistics	CLUE (Conversion of Land Use and its Effects)	Verburg et al. (1999)	land use model	EU 27

The majority of dynamic vegetation models utilize the concept of plant functional types (PFTs), which divide vegetation patterns into broad biome categories (Prentice et al., 1992). As PFTs or biomes reflect environmental gradients and interactions, they do not include wetland information due to the azonal characteristics of most wetlands (Walter & Breckle, 1991). Within the borders of vegetation occurrence, climate – as a main driver of wetland existence (through precipitation) – only plays a role for certain wetland types, such as bogs and several types of swamp forests. Usually, climate variables, such as temperature and precipitation, can be fed into any vegetation model, which produces a vegetation cover for the corresponding climate (Wang, 2002). In contrast to other vegetation formations that can be aggregated to climate-dependent biomes, many more variables are needed to integrate wetlands into such models and evaluate potential changes. Wang (2002) and Cramer (2002) have both provided comprehensive overviews of dynamic vegetation models. In some models (e.g. CLM4), wetlands are included separately in the PFTs and afterwards are categorized as non-vegetated areas without soil properties, together with urban areas or glaciers. These non-vegetated land cover fractions are held constant throughout the time series.

The majority of existing models are applied on the global scale with coarse resolutions, with only a few models in existence that cover Europe. These applications mainly use aggregated or original CORINE land cover information (EEA, 2000), or integrate models such as IMAGE or CLUE (Klijn et al., 2005) to obtain information on land cover or vegetation. The European-scale SWEDI model (Schleupner, 2010), which concentrates explicitly on wetlands, has been implemented in two models so far. However, as with global wetland datasets, SWEDI only covers present wetland distributions.

3.2.2. Modeling Wetland Distribution

This subsection gives an overview of existing freshwater wetland distribution models and tools to model wetlands. Such models are useful for projecting climate change effects on wetland systems, as well as in adaptation planning of resilient wetland habitat networks (Erwin, 2009). The topic of wetland modeling is complex. The ISI Web of Knowledge alone lists around 3,000 articles when searching for the phrase “modeling wetlands”, demonstrating that, on the whole, studies on freshwater wetland distribution modeling are reasonable in number. However, most of these studies concentrate on certain wetland species or chemical wetland components at local scales, and there is an additional strong focus on marine and coastal wetlands.

In general, wetland distribution is modeled at all scales from global (Prigent et al., 2007; Stacke & Hagemann, 2010), over continental (Merot et al., 2003; Decharme et al., 2008; Fan & Miguez-Macho, 2010), to the catchment level (Miola et al., 2006; Milzow et al., 2010). Within these differently scaled approaches, several studies have focused on the distribution of wetlands during the last glacial maximum (Carrington et al., 2001; Kaplan, 2002; Miola et al., 2006), while others have incorporated present climate and hydrological conditions into the wetland models used (Walter et al., 2001; Merot et al., 2003; Yu et al., 2006). Only a minority has tended to use a combination of future climate and development scenarios; Milzow et al. (2010) is a good example.

The primary factors determining wetland distributions are water (precipitation, surface water, and groundwater) and land topography (Rodhe & Seibert, 1999; Fan & Miguez-Macho, 2010) which, in combination with other geophysical and climate parameters, set the various wetland types (Tiner, 2009b). Hydrology-based models of any kind that include these factors are utilized as a base input for the identification of overall wetland distribution. Water budget models in particular, which can be used to delineate wetlands at the watershed scale, are common. One of these models is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1999), which incorporates surface and groundwater interactions. Numerous studies have been performed all over the world in which this tool has been applied; indeed, an online database that provides an overview of

SWAT-based literature (https://www.card.iastate.edu/swat_articles/) lists 673 peer-reviewed journal articles on the topic. Other tools helpful in identifying wetlands at the watershed scale are TOPMODEL (Beven & Kirkby, 1979), which is based on the soil wetness index (Güntner et al., 2004), MIKE-SHE (Graham & Butts, 2006), the Wetland Dynamic Water Budget Model (WDWBM, Walton et al., 1996), the groundwater flow model MODFLOW (Harbaugh et al., 2000), and the eco-hydrological modeling system ArcEGMO (http://www.arcegmo.de), to name just a few. A more detailed overview of wetland modeling can be found in Ji (2007).

Silberstein (2006) analyzed the performance of hydrological models. Due to their orientation at the watershed scale, applications of these models at the broader continental scale have so far hardly ever been tackled (Arnold et al., 1999; Schuol & Abbaspour, 2006), and within these hydrology-oriented studies wetland delineation and characterization receives little attention. Furthermore, hardly any research has been undertaken on potential changes in groundwater systems and their effects on wetlands (Erwin, 2009). Recent dynamic global inundation or wetland models (Prigent et al., 2007; Stacke & Hagemann, 2010) are too coarse and aggregated for applications in studies at the European scale. In addition, they do not take into account any past or future anthropogenic modifications to terrestrial ecosystems. Studies on wetland distribution modeling applied at continental or broad regional scales are therefore the main focus of this review. Five studies match these criteria (Carrington et al., 2001; Yu et al., 2006; Anyah et al., 2008; Decharme et al., 2008; Fan & Miguez-Macho, 2010), of which only one study (Fan & Miguez-Macho, 2010) concentrates explicitly on wetlands. The others focus mainly on hydrologic simulations. No article describes the modeling of wetland distributions over Europe.

Often, bioclimatic envelope models are used to describe potential changes in habitat delineation, and Heikkinen et al. (2006) provides a comprehensive overview of the application of these models. Some recent studies use the methods of bioclimatic envelope models, artificial neural networks, or other regression-based modeling approaches, to evaluate potential effects of climate changes on certain wetland species (Araújo et al., 2006; Kennedy et al., 2006; Harrison et al., 2008). However, one should not forget that wetlands are usually fed by waters that have accumulated in a catchment area upstream. Therefore, the whole catchment area should be taken into consideration in the modeling of wetland distribution (Costa et al., 1996). Further, many factors other than climate define the range of a species and should be taken into consideration (Heikkinen et al., 2006). Other studies have shown that the performance of bioclimatic models not only depends on a considerable amount of knowledge concerning the factors influencing the accuracy of the model performance, but also on the characteristics of the species (Heikkinen et al., 2006; Marmion et al., 2009). Thus, bioclimatic envelope models are less suitable for modeling spatial wetland distribution per se. They may, though, be of interest in modeling changes of species composition and distribution within modeled dynamic wetland borders. However, the first step in wetland habitat delineation is the understanding of the processes that lead to alternative trajectories and distributions of habitat types. The following section provides an overview of existing studies on European freshwater wetlands, climate drivers and ecological responses.

3.3. Effects of Change on European Wetland Distributions

Wetlands are dynamic ecosystems on the margins between terrestrial and aquatic land. Thus, they are not static in space or time. In Europe, wetlands have mainly remained on fragmented sites within a highly modified environment. The question for sustainable conservation adaptation planning is how these wetlands may cope with changing climate conditions. Parish et al. (2008) further point out that the response of wetlands to changes is unlikely to be smooth and monotonic, but will instead happen through the crossing of thresholds, beyond which changes are sudden and perhaps irreversible. As palaeo-environmental studies have shown (Parish et al., 2008), peat accumulation may be interrupted for several hundred years by events such as fires, floods, or long-term droughts. The identification of these thresholds may thus be a major task for future research.

Wetlands are vulnerable to changes in quantity and quality of their water supply (Erwin, 2009). One potential effect of climate change might be changes in physical drivers, such as more extreme floods and droughts, higher water temperatures etc.; but also of importance are biological effects, such as changes in species abundance and ecosystem structure (Wilby et al., 2010). As wetlands are mainly influenced by mechanisms of water supply and storage (Bartsch et al., 2009), the modeling of climate change impacts on wetlands has to take wetland–water relationships into account. In this regard, knowledge of the water level requirements of species is important in the understanding of possible future habitat composition (Dawson et al., 2003). However, whereas the upper limit of wetland wetness is clearly permanent inundation or saturation to the surface, much uncertainty exists around the definition of minimum wetness of wetlands (Tiner, 2009b).

The U.S. Army Corps of Engineers (1997) gives the following definition: “An area has wetland hydrology when it is saturated within one foot (~ 30 cm) of the soil surface for two weeks or more during the growing season in most years (about every other year on average)”. According to Wheeler (1999), the most discriminating variables for the occurrence of plant communities are the mean highest and lowest groundwater levels during the growing season. We identified numerous published papers within our review on the effects of changes on European wetlands. Most of the studies reported upon in these works were conducted on sites outside of Europe; namely, the USA or China. While these studies may well be useful as a surrogate for European wetlands, thus helping to bridge the knowledge gap, they were not included in our review. The majority of studies focus upon open water river and lake systems, and not on adjacent wetland ecosystems per se (Durance & Ormerod, 2007; Franklin et al., 2008; Johnston et al., 2009; Mooij et al., 2009). Conlan et al. (2007) evaluated climate change impacts on macro-invertebrates living in streams in Yorkshire and Wales by utilizing their optimum and amplitude ranges of occurrence. Even if this research was fundamental for the understanding of changes in quality and quantity of adjacent wetlands, the distributional effects on these wetlands have yet to be accounted for. Only a few studies have dealt with the understanding of the environmental preferences and limits of wetland species (Wilby et al., 2010), and only a minority of these was developed in Europe. For example, Ellenberg et al. (1979, 1991) listed indicator values for Central Europe that indicate the tolerances of certain species to mean water tables. Hill et al. (1999) did the same for the UK and Ireland. Harrison et al. (2008) used these Ellenberg indicator values for selected fen and bog species to project changes in wetlands for Britain, while Klotz et al. (2002)

developed a database with biologic–ecologic indicators for the flora of Germany. Henle et al. (2006) developed and applied methodologies to define ecological indicators of species–environment relationships of Central European floodplain species.

Table 3 lists articles dealing with the effects of changes on wetlands. Most of them concentrate on what are clearly climate-dependent wetland types like palsa mires in Scandinavia (e.g. Fronzek et al., 2009) or bogs in the UK (Harrison et al. 2008). Drought-affected Mediterranean wetlands (Castañeda et al., 2005) are also a focus among these studies, and a further feature is the modeling of species distributions as indicators of wetland distributional changes (Dawson et al., 2003). Whereas studies on wetland functions also exist (e.g. Maltby et al., 1996), studies on the relationships between wetland persistence and climate, such as that produced by Keith et al. (2010) for Australian wetlands, were not found for Europe. Nor were comparable studies found for Europe on the linkage of hydrological dynamics with wetland vegetation distribution, as conducted by Todd et al. (2010) in the Everglades National Park.

Table 3. Studies on changes of wetlands

author	region covered	wetland type	comments
Araújo et al. (2006)	Europe		amphibians and reptiles bioclimatic-envelope modeling, 50*50 km grid
Boix et al. (2010)	Mediterranean region	aquatic river species	the recovery of biological communities from drought depends on the type of hydrological event, the environment characteristics, the existence of refugia, and the taxonomic group concerned
Castañeda et al. (2005)	Monegros desert, Spain	playa lakes	detection of future disturbance, effects of changes in natural hydrological regime on wetlands, such as increased flooding surface area and habitat degradation by fresh and polluted water flow inputs.
Dawson et al. (2003)	Great Britain and Ireland	rain-fed wet meadow	selected species distributions species composition of wetlands will change in response to changing climate and hydrology
Fronzek et al. (2009)	Sub-artic Fennoscandia	palsa mires	aims: to map the current distribution of palsa mires, to model future changes in palsa mire distribution due to projected climate warming, to estimate future changes in

			the CH_4 and CO_2 budgets of palsa mires; and to assess the ecosystem implications of palsa mire degradation and investigate possible conservation measures.
Gascón et al. (2009)	Mediterranean region	aquatic species of Mediterranean wetlands	aims: to compare the response of 11 biodiversity metrics in order to know which ones are redundant, to identify key environmental factors for biodiversity, and to find out whether sites with high biodiversity values also have a good habitat condition and high protection status.
Harrison et al. (2008)	Britain	fen and bog species	species distribution SPECIES model: artificial neural network, utilizing Ellenberg indicator values
Henle et al. (2006)	Middle Elbe, Germany	floodplain species of periodically flooded grasslands	impacts of biodiversity under altered hydrological regimes species-environment relationships, ecological indicators, RIVA project
Hills et al. (1994)	Europe	riverine wetland ecosystems	method for classifying European riverine wetland ecosystems using functional vegetation groupings
Kennedy & Murphy (2003)	Scotland	floodplain wetland	hydrological and hydrochemical conditions characterising Carex habitat in a Scottish floodplain wetland.
Kennedy et al. (2006)	Scotland/northern England	freshwater wetlands	effects of vegetation to hydrological driving factors regression based modeling approach
Melendez-Pastor et al. (2010)	south-east Spain	artificial Mediterranean wetland	land-cover changes are analyzed for a drought-affected hydrologic year (2004–2005) in comparison to an average hydrologic year (2000–2001) by means of remote sensing techniques
Murphy et al. (1994)		riverine wetlands	biotic indicators of riverine wetland ecosystem functioning
Strack (2008)	global case studies	peatlands	the role of peatlands and peat within the current context of global climate change
Vervuren et al. (2003)	Rhine	riparian wetlands	survival and distribution of plant species due to extreme flooding events
Zuidhoff (2002)	northern Sweden	palsa mire	decay of single palsa in relation to weather conditions time period: 1996-2000

4. Discussion

Wetland inventories and existing data on wetlands in the European landscape. Comprehensive and consistent inventory data of wetland spatial distribution in Europe are nonexistent. Wetland inventories provide national estimates rather than verified values. Therefore, international, and even intranational comparisons of existing data are difficult and should only be taken with precaution. Initiatives such as those developed by Ramsar and MedWet have tried to overcome these problems, and in this regard earth observation techniques play an important role in the comprehensive delineation of wetlands. In particular, the evaluation of relative soil moisture through earth observation provides the potential to account for external hydrological factors of wetland ecosystems (Bartsch et al., 2009). Regular measurements of global soil moisture are available from scatterometer data at resolutions of 25–50 km (Wagner et al., 2003), but comprehensive continental data for Europe have not yet been produced, and Fernandez-Prieto et al. (2006) and Tiner (2009) pointed out that there are many wetland types that may not be easily identified through such technology (e.g. certain evergreen forested wetland types and partly drained wetlands). Presently, the SWEDI database (Schleupner, 2010) offers spatial data for European wetlands compiled from existing data sources. However, estimations of the overall extent of European wetlands remain controversial and incomparable.

Wetland distributions in models and models of wetland distributions. Costanza & Sklar (1985) provided an earlier review of freshwater wetland models and their effectiveness. They reported that even though a large number of models existed, only very few were able to be spatially explicit. Our review has found that, within earth system models, wetlands are included as static shapes with fixed boundaries. Also, for European studies, existing global-scale wetland distribution data are often used, most recently including the SWEDI database.

Wetlands are modeled at all scales. However, existing approaches to modeling wetlands globally are too coarse and aggregated for European-scale studies and do not take anthropogenic changes into consideration. The majority of studies have focused on the catchment scale, where ecohydrological models can be applied, but these models are not suitable for broader-scaled analyses. Thus, few studies have modeled wetland distributions at the continental scale. A particular difficulty for ecological wetland models is that of matching spatiotemporal scales of both hydrologic and biological processes (Fitz, 2008). Davidson and Finlayson (2007) therefore postulated to conduct multiple-scale approaches. The use of future scenarios to evaluate changes in wetland extent and distribution is an important topic in sustainable wetland conservation planning. However, there is a clear lack of such studies at all scales. Bioclimatic envelope models are useful for the evaluation of range shifts of certain species under changing climates, but they are not applicable in the evaluation of changes of wetland distribution irrespective of changes in species composition. Additionally, the impact of climate change on non-coastal wetlands is uncertain and difficult to evaluate because of uncertainties in climate and precipitation projections.

Ecosystem resilience and effect of wetlands under climate change. For appropriate wetland modeling the primary goal should be the understanding of fundamental physical, chemical, and biological interactions within wetlands. Subsequently, potential wetland distribution under changing conditions can be projected. As the number of research papers demonstrates, coastal wetlands and aquatic waters have so far received more attention than the semi-terrestrial wetlands. There is a lack of studies addressing species–environment and cause–effect relationships in wetlands, not only in Europe. For example, knowledge of the water level requirements of species is an important component for understanding possible future habitat composition (Dawson et al., 2003). The development of indicator systems might help to understand the environmental relationships in complex ecosystems such as floodplains, which are determined by parameters and processes that are difficult to measure directly (Henle et al., 2006).

Another component is the evaluation of wetland thresholds that may lead to sudden changes in wetland composition or distribution (Parish et al., 2008). Drivers, pressures, and wetland responses to these are still not well understood. Studies on European wetland persistence and climate change are not available, but highly recommended.

General remarks. Climate change is only one of many factors affecting wetlands. Its impacts may be exacerbated by other human pressures, including habitat loss, pollution, and invasive species (Millenium Ecosystem Assessment, 2005; Wilby et al., 2010). Therefore, wetland models need to include at least land use changes. In Europe, land use change and climate change are both key drivers of wetland change and interactions between these drivers are complex and currently not well understood (Lepers et al., 2005; de Chazal & Rounsevell, 2009). Human disturbance to peatlands often makes them much more vulnerable to climate change impacts, as Parish et al. (2008) noted. These factors need to be analyzed in combination rather than in isolated studies (de Chazal & Rounsevell, 2009). There remains much uncertainty about species and ecosystem level responses to the combined effect of climatic and non-climatic pressures (Wilby et al., 2010). Therefore, strategies have to deal with these uncertainties in addressing adaptation options (Ormerod, 2009; Wilby et al., 2010).

Shifts in wetland habitat may also have important implications on surface water hydrology, through feedbacks of vegetative resistance to flow, local evapotranspiration demands, or organic sediment accumulation and topographic patterns (Fitz, 2008). It is certain that wetlands play an important role in the regulation of atmospheric gases and groundwater flow. They can serve as carbon sinks or sources depending on their utilization. Despite advances in research, wetlands remain one of the biggest unknowns of the near future regarding element dynamics and matter fluxes (Paul et al., 2006; Erwin, 2009), and the role of wetlands in the global carbon cycle is poorly understood (Maltby et al., 2003). Knowledge of long-term wetland dynamics also helps in the more precise estimation of the contribution of wetlands to the carbon cycle and greenhouse gas emissions.

5. Conclusion

As demonstrated in this review, there is very little knowledge surrounding the effects of climate change on wetland distribution and composition. Particularly in Europe, there is a fundamental lack of knowledge on wetland ecosystem functions, processes, as well as their spatial and temporal distributions under changing conditions. Consequently, the ability to project wetland distributional changes is still limited. Therefore, the main conclusion to be drawn from this review is the need to produce more process-based information for model development. This should include data on existing wetland distribution, environmental state, and habitat suitability. More studies such as that conducted by Keith et al. (2010) on the relationship between wetland persistence and climate need to be carried out, not only in Europe, and at all spatial scales. Knowledge about the future extent of wetlands is of importance, especially for adaptation planning. Advances in wetland distribution modeling will thus help to improve the resilience of wetland ecosystems, such that they continue to provide important services, even under changes in climate conditions.

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6. References

Aber JS, Marzolff I & Ries JB (2010) Wetland Environments. *Small-Format Aerial Photography*, 201-212.

Alexandridis TK, Lazaridou E, Tsirika A & Zalidis GC (2009) Using Earth Observation to update a Natura 2000 habitat map for a wetland in Greece. *Journal of Environmental Management* **90**, 2243-2251.

Alcamo J & Henrichs T (2002) Critical regions: a model-based estimation of world water resources sensitive to global changes. *Aquatic Science* **64**, 1–11.

Alkemade R, Van Oorschot M, Miles L, Nellemann C, Bakkenes M & ten Brink B (2009) GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems* **12**, 374 – 390.

Anyah RO, Weaver CP, Miguez-Macho G, Fan Y & Robock A (2008) Incorporating water table dynamics in climate modelling: 3. simulated groundwater influence on coupled land-atmosphere variability. *Journal of Geophysical Research* doi:10.1029/2007JD009087

Araújo MB, Thuiller W & Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. *Journal of Biogeography* **33**, 1712-1728.

Arnold JG, Srinivasan R, Muttiah RS & Allen PM (1999) Continental Scale Simulation of the Hydrologic Balance. *Journal of the American Water Resources Association* **35** (5), 1037-1051.

Aselmann I & Crutzen PJ (1989) Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. *Journal of Atmospheric Chemistry* **8** (4), 307-358.

Bachelet D, Lenihan JM, Daly C, Neilson RP, Ojima DS & Parton WJ (2001) MC1: A Dynamic Vegetation Model for Estimating the Distribution of Vegetation and Associated Ecosystem Fluxes of Carbon, Nutrients, and Water. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-508

Bartsch A, Wagner W, Scipal K, Pathe C, Sabel D & Wolski P (2009) Global monitoring of wetlands – the value of ENVISAT ASAR Globe mode. *Journal of Environmental Management* **90**, 2226-2233.

Bates BC, Kundzewicz ZW, Wu S & Palutikof JP (2008) (Eds.) Climate Change and Water. Technical Paper VI of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva. Available via: http://www.ipcc.ch/pdf/technicalpapers/climate-change-water-en.pdf.

Beven KJ & Kirkby MJ (1979) A physically based, variable contributing area model of basin hydrology. *Hydrological Science Bullentin* **24**,43–69.

Bohn U & Neuhäusel R, with contributions by Gollub G, Hettwer C, Neuhäuslová Z, Raus T, Schlüter H & Weber H (2003) Karte der natürlichen Vegetation Europas / Map of the Natural Vegetation of Europe. Scale 1 : 2 500 000. Landwirtschaftsverlag, Münster.

Boix D, García-Berthou E, Gascón S, Benejam L, Tornés E, Sala J, Benito J, Munné A, Solà C & Sabater S (2010) Response of community structure to sustained drought in Mediterranean rivers. *Journal of Hydrology* **383**, 135–146.

Bonan GB, Levis S, Sitch S, Vertenstein M & Oleson KW (2002) A dynamic global vegetation model for use with climate models: concepts and description of simulated vegetation dynamics. *Global Change Biology* **9**, 1543 – 1566.

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W & Gerten D (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* **13**(3), 679–706.

Boumans R, Costanza R, Farley J, Wilson MA, Portela R, Rotmans J, Villa F & Grasso M (2002) Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model. *Ecological Economics* **41**, 529–560.

Bouwman AF, Kram T & Klein Goldewijk K (2006) (Eds.) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment agency. Bilthoven, The Netherlands.

Brovkin V, Ganopolski A & Svirezhev Y (1997) A continuous climate-vegetation classification for use in climate-biosphere studies. *Ecological Modelling* **101**, 251-261.

Cai X & Ji W (2009) Wetland hydrologic application of satellite altimetry – A case study in the Poyang Lake watershed. *Progress in Natural Science* **19,** 1781–1787.

Carrington DP, Gallimore RG & Kutzbach JE (2001) Climate sensitivity to wetlands and wetland vegetation in mid-Holocene North America. *Climate Dynamics* **17**,151–157.

Castañeda C, Herrero J & Auxiliadora Casterad M (2005) Landsat monitoring of playa-lakes in the Spanish Monegros desert. *Journal of Arid Environments* **63**, 497–516.

Cogley J (2003) GGHYDRO-Global Hydrographic Data, release 2.3. Tech. Not. 2003-1, Dept. of Geogr., Trent Univ., Peterborough, Ont., Canada.

Conlan K, Lane S, Ormerod S & Wade T (2007) Preparing for climate change impacts on freshwater ecosystems (PRINCE): results. Science Report to Environment Agency No. SC030300/SR.

Costa LT, Farinha JC, Hecker N & Tomàs-Vives P (1996) Mediterranean wetland inventory: A Reference Manual. MedWet / Instituto da Conservacao da Natureza / Wetlands International Publication, Volume I.

Costanza R & Sklar FH (1985) Articulation, Accuracy and Effectiveness of Mathematical Models: A Review of Freshwater Wetland Applications. *Ecological Modelling* **27**, 45-68.

Cox PM (2001) Description of the "TRIFFID" Dynamic Global Vegetation Model. Hadley Centre technical note 24, Bracknell, Berks, RG122SY, UK.

Cramer W (2002) Biome Models. Volume 2, The Earth system: biological and ecological dimensions of global environmental change. In: HA Mooney & JG Canadell (Eds.) Encyclopedia of Global Environmental Change, John Wiley & Sons, Ltd, Chichester, pp. 166–171.

Darras S, Michou M & Sarrat C (1999) IGBP-DIS Wetland Data Initiative: a First Step Towards Identifying a Global Delineation of Wetlands. IGBP-DIS Office, Toulouse, France.

Davidson NC & Finlayson CM (2007) Earth Observation for wetland inventory, assessment and monitoring. *Aquatic Conservation: Marine and Freshwater Ecosystems* **17**, 219-228.

Dawson TP, Berry PM & Kampa E (2003) Climate change impacts on freshwater wetland habitats. *Journal for Nature Conservation* **11**, 25-30.

Decharme B, Douville H, Prigent C, Papa F & Aires F (2008) A new river flooding scheme for global climate applications:off-line evaluation over South America. *Journal of Geophysical Research* **113**, doi:10.1029/2007JD009376

de Chazal J & Rounsevell MDA (2009) Land-use and climate change within assessments of biodiversity change: a review. *Global Environmental Change* **19**, 306-315.

Drösler M, Freibauer A, Christensen TR, Friborg T (2008) Observations and Status of Peatland Greenhouse Gas Emissions in Europe. In: AJ Dolman, R Valentini & A Freibauer (Eds.) The Continental-Scale Greenhouse Gas Balance of Europe. Springer, New York, pp. 243-261.

Durance I & Ormerod SJ (2007) Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology* **13**, 942–57.

Ellenberg H (1991) Zeigerwerte von Gefässpflanzen Mitteleuropas. *Scripta Geobotanica* **9**, 1–122.

Ellenberg H, Weber HE, Düll R, Wirth V, Werner W & Paulissen D (1979) Zeigerwerte von Gefässpflanzen Mitteleuropas. *Scripta Geobotanica* **18**, 1–248.

Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecological Management* **17**, 71-84.

European Commission (2003) Global Land Cover 2000 database. Joint Research Centre. http://gem.jrc.ec.europa.eu/products/glc2000/glc2000.php

European Commission (2004) European Soil Database (v 2.0). European Soil Bureau Network and the European Commission, EUR 19945 EN, March 2004. Joint Research Centre Institute for Environment and Sustainability

European Commission (2006) Communication from the Commission to the Council and the European Parliament - Renewable energy road map - Renewable energies in the 21st century: building a more sustainable future. /* COM/2006/0848 final */

European Commission (2010) Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Options for an EU vision and target for biodiversity beyond 2010. Available via http://ec.europa.eu/environment/nature/biodiversity/policy/pdf/communication_2010_0004.pdf

EEA (2000) (Ed.) CORINE Land Cover 2000 Database, 100 m. Available via http://dataservice.eea.eu.int/dataservice.

Fan Y & Miguez-Macho G (2010) A simple hydrologic framework for simulating wetlands in climate and earth system models. *Climate Dynamics* DOI 10.1007/s00382-010-0829-8.

Fernandez-Prieto D, Arini O, Borges T, Davidson N, Finlayson M, Grassl H, MacKay H, Prigent C, Pritchard D & Zalidis G (2006) The GlobWetland Symposium: Summary and Way Forward. Proceedings Glob-Wetland: Looking at Wetlands from Space, October 2006, Frascati, Italy.

Finlayson CM & Spiers AG (1999) Global Review of Wetland Resources and Priorities for Wetland Inventory – GroWI. Available via: http://www.wetlands.org/RSIS/WKBASE/GRoWI/welcome.html

Finlayson CM, D'Cruz R & Davidson NJ (2005) Ecosystem Services and Human Well-being: Water and Wetlands Synthesis. World Resources Institute, Washington DC, USA.

Fitoka E & Keramitsoglou I (2008) (Eds.) Inventory, assessment and monitoring of Mediterranean Wetlands: Mapping wetlands using Earth Observation techniques. EKBY & NOA. MedWet publication.

Fitz HC (2008) Wetland Models. *Encyclopedia of Ecology*, 3780-3790.

Franklin P, Dunbar M & Whitehead P (2008) Flow controls on lowland river macrophytes: a review. *Science of the Total Environment* **400**, 369–78.

Friend AD, Stevens AK, Knox RG & Cannell MGR (1997) A Process-based, Terrestrial Biosphere Model of Ecosystem Dynamics (Hybrid v3.0), *Ecological Modelling* **95**, 249–287.

Fronzek S, Johansson M, Christensen TR, Carter TR, Friborg T & Luoto M (2009) (Eds.) Climate change impacts on sub-arctic palsa mires and greenhouse gas feedbacks. Proceedings of the PALSALARM symposium, Abisko, Sweden, 28-30 October 2008. *Reports of the Finnish Environment Institute* 3/2009, 74 p. Finnish Environment Institute.

Gascón S, Boix D & Sala J (2009) Are different biodiversity metrics related to the same factors? A case study from Mediterranean wetlands. *Biological Conservation* **142**, 2602–2612.

German Ramsar National Report (1998) Übersicht der Ramsar-Gebiete in Deutschland. WWF Deutschland, Frankfurt a M.

GEO Secretariat (2009) GEO VI. GEOSS Strategic Targets. Doc 12 (rev1), http://www.earthobservations.org/

Graham DN & Butts MB (2006) Flexible, integrated watershed modelling with MIKE. In: VP Singh & DK Frevert (Eds.) Watershed Models, CRC Press, Boca Raton, pp. 245–272.

Güntner A, Seibert J & Uhlenbrook S (2004) Modeling spatial patterns of saturated areas: an evaluation of different terrain indices. *Water Resources Research* **40**, 1-19.

Harrison PA, Berry PM, Henriques C & Holman IP (2008) Impacts of socio-economic and climate change scenarios on wetlands: linking water resource and biodiversity meta-models. *Climatic Change* **90**, 113-139.

Harbaugh AW, Banta ER, Hill MC & McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the Ground-Water Flow Process. USGS Open-File Report 00-92. Reston, Virginia: U.S. Geological Survey.

Heikkinen R K, Luoto M, Araújo MB, Virkkala R, Thuiller W & Sykes MT (2006) Methods and uncertainties in bioclimatic envelope modelling under climate change. *Progress in Physical Geography* **30**, 751–777.

Henle K, Dziock F, Foeckler F, Follner K, Hüsing V, Hettrich A, Rink M, Stab S & Scholz M (2006) Study Design for Assessing Species Environment Relationships and Developing Indicator Systems for Ecological Changes in Floodplains – The Approach of the RIVA Project. *International Reviews of Hydrobiology* **91**, 292-313.

Hill MO, Mountford JO, Roy DB & Bunce RGH (1999) Ellenberg's indicator values for British plants. Ecofact volume 2 Technical Annex. Institute of Terrestrial Ecology, Department of Environment Transport and the Regions, London.

Hills J M, Murphy KJ, Pulford ID & Flowers TH (1994) A method for classifying European riverine wetland ecosystems using functional vegetation groupings. *Functional Ecology* **8**, 242–252.

Irish Peatland Conservation Council (1998) Peatlands around the world. Available via http://www.ipcc.ie/

Jantke K & Schleupner C (2010) Gap Analysis of European Wetland Species - a Method to Work with Coarse Scale Biodiversity Data. Presented at 24th International Congress for Conservation Biology, Edmonton (Alberta), Canada, July 3-7.

Ji W (2007) (Ed.) Wetland and Water Resource Modeling and Assessment: A Watershed Perspective. CRC Press, New York.

Jones K, Lanthier Y, van der Voet P, van Valkengoed E, Taylor D & Fernández-Prieto D (2009) Monitoring and assessment of wetlands using Earth Observation: The GlobWetland project. *Journal of Environmental Management* **90**, 2154-2169.

Johnston AC, Acreman MC, Dunbar MJ, Feist SW, Giacomello AM, Gozlan RE, Hinsley SA, Ibbotson AT, Jarvie HP, Jones JI, Longshaw M, Maberly SC, March TJ, Neal C, Newman JR, Nunn MA, Pickup RW, Reynard NS, Sullivan CA, Sumpter JP & Williams RJ (2009) The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of The Total Environment* **407** (17), 4787-4798.

Joosten H & Clarke D (2002) Wise use of Mires and Peatlands. International Mire Conservation Group & International Peat Society NHBS Ltd., Totnes.

Kaplan JO (2002) Wetlands at the last glacial maximum: distribution and methane emissions. *Geophysical Research Letters* doi:10.1029/2001GL013366

Keith DA, Rodoreda S & Bedward M (2010) Decadal change in wetland–woodland boundaries during the late 20th century reflects climatic trends. *Global Change Biology* **16**, 2300–2306.

Kennedy MP & Murphy KJ (2003) Hydrological and hydrochemical conditions characterising Carex chordorrhiza L. fil. (String Sedge) habitat in a Scottish floodplain wetland. *Aquatic Botany* **77**, 243–255.

Kennedy MP, Murphy KJ & Gilvear DJ (2006) Predicting interactions between wetland vegetation and the soil-water and surface-water environment using diversity, abundance and attribute values. *Hydrobiologia* **570**, 189–196.

Keramitsoglou I, Sarimveis H, Kiranoudis CT & Sifakis N (2005) Radial Basis Function neural networks classification using very high spatial resolution satellite imagery: An application to the habitat area of Lake Kerkini (Greece). *International Journal of Remote Sensing* **26** (9), 1861–1880.

Kleinod K, Wissen M & Bock M. (2005) Detecting vegetation changes in a wetland area in Northern Germany using earth observation and geodata. *Journal for Nature Conservation* **13** (2005), 115-125.

Klijn JA, Vullings LAE, vd Berg M, van Meijl H, van Lammeren R, van Rhenen T, Tabeau AA, Veldkamp A, Verburg PH, Westhoek H & Eickhout B (2005) The EURURALIS study: Technical document. Alterra-rapport 1196, Wageningen.

Klotz S, Kühn I & Dukra W (2002) BIOLFLOR – Eine Datenbank mit biologisch-ökologischen Merkmalen zur Flora von Deutschland. *Schriften zur Vegetationskunde* **38**, 1–334.

Kucharik CJ, Barford CC, El Maayar M, Wofsyc SC, Monsond RK & Baldocchie DD (2006) A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO2 and H2O vapor exchange. *Ecological Modeling* **196**, 1–31.

Lehner B & Döll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* **296** (1-4), 1-22.

Lepers E, Lambin EF, Janetos AC, Defries R, Achard F, Ramankutty N & Scholes RJ (2005) A synthesis of information on rapid land-cover change for the period 1981–2000. *Bioscience* **55** (2), 115–124.

MacKay H, Finlayson CM, Fernández-Prieto D, Davidson N, Pritchard D & Rebelo L-M (2009) The role of Earth Observation (EO) technologies in supporting implementation of the Ramsar Convention on Wetlands. *Journal of Environmental Management* **90**, 2234-2242.

Maltby E, Hogan DV & McInnes RJ (1996) Functional Analyses of European Wetland Ecosystems – Phase I (FAEWE). European Commission (*Ecosystem Research Report* **18**), Brüssel.

Maltby E, Sgouridis F, Négrel P, Petelet-Giraud E (2003) Integration of European Wetland research in sustainable management of the water cycle – EUROWET Technical Guidance. Available via: http://www.ufz.de

Marmion M, Luoto M, Heikkinen RK & Thuiller W (2009) The performance of state-of-the-art modelling techniques depends on geographical distribution of species. *Ecological Modelling* **220**, 3512-3520.

Matthews E & Fung I (1987) Methane Emission from Natural Wetlands: Global Distribution, Area, and Environmental Characteristics of Sources. *Global Biogeochemical Cycles GBCYEP* **1** (1), 61-86.

Melendez-Pastor I, Navarro-Pedreno J, Gómez I & Koch M (2010) Detecting drought induced environmental changes in a Mediterranean wetland by remote sensing. *Applied Geography* **30**, 254–262.

Merot P, Squividant H, Aurousseau P, Hefting M, Burt T, Maitr V, Kruk M, Butturini A, Thenail C & Viaud V (2003) Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. *Ecological Modelling* **163** (1-2), 51-71.

Metzger MJ, Bunce RGH, Leemans R & Viner D (2008) Projected environmental shifts under climate change: European trends and regional impacts. *Environmental Conservation* **35**, 64–75.

Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Milzow C, Burg V & Kinzelbach W (2010) Estimating future ecoregion distributions within the Okavango Delta Wetlands based on hydrological simulations and future climate and development scenarios. *Journal of Hydrology* **381**, 89-100.

Miola A, Bondesan A, Corain L, Favaretto S, Mozzi P, Piovan S & Sostizzo I (2006) Wetlands in the Venetian Po Plain (northeastern Italy) during the last glacial maximum: interplay between vegetation, hydrology and sedimentary environment. *Rev Palaeobot Palynol* **141**(1–2), 53–81.

Mitra S, Wassmann R & Vlek PLG (2005) An appraisal of global wetland area and its organic carbon stock. *Current Science* **88** (1), 25-35.

Moser M, Prentice C & Frazier S (1996) A global overview of wetland loss and degradation. Proceedings to the 6th meeting of the Conference of Contracting Parties of the Ramsar Convention 10.

Mooij WM, De Senerpont Domis LN, Janse JH (2009) Linking species- and ecosystem-level impacts of climate change in lakes with a complex and a minimal model. *Ecological Modelling* **220** (21), 3011-3020.

Moss D & Davies C (2002 a) Cross-references between EUNIS habitat classification and the Habitats Directive. European Topic Centre on Nature Protection and Biodiversity, Paris.

Moss D & Davies C (2002 b) Cross-references between the EUNIS habitat classification and the nomenclature of the CORINE land cover. CEH project CC00389.

Mulamoottil G, Warner BG & McBean EA (1996) Wetlands: Environmental Gradients, Boundaries and Buffers. Lewis Publishers, New York.

Murphy KJ, Castella E, Clement B, Hills JM, Obrdlik P, Pulford ID, Schneider E & Speight MCD (1994) Biotic indicators of riverine wetland ecosystem functioning. In: WJ Mitsch (Ed.) Global Wetlands: Old World and New. Elsevier, Amsterdam, pp. 659–682.

Murphy PNC, Ogilvie J, Connor K & Arp PA (2007) Mapping Wetlands: A Comparison of two different approaches for New Brunswick, Canada. *Wetlands* **27** (4), 846-854.

Niu ZG, Gong P, Cheng X, Guo JH, Wang L, Huang HB, Shen SQ, Wu YZ, Wang XF, Wang XW, Ying Q, Liang L, Zhang LN, Wang L, Yao Q, Yang ZZ, Guo ZQ & Dai YJ (2009) Geographical characteristics of China's wetlands derived from remotely sensed data. *Science of China Series D-Earth Sciences* **52** (6), 723-738.

Nivet C & Frazier S (2004) A review of European wetland inventory information. Report prepared in the framework of “A pilot study towards a Pan-European wetland inventory”. In: ARD Taylor & M van Eerden (Eds.) Wetlands International (RAMSAR).

Oleson KW, Lawrence DM, Bonan GB, Flanner MG, Kluzek E, Lawrence PJ, Levis S, Swenson SC & Thornton PE (2010) Technical Description of version 4.0 of the Community Land Model (CLM). NCAR Technical Note, Boulder, Colorado, USA.

Ormerod SJ (2009) Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems* **19,** 609-613.

Parish F, Sirin A, Charman D, Joosten H, Minayeva T, Silvius M & Stringer L (2008) (Eds.) Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ & Hanson CE (2007) (Eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Paul S, Jusel K & Alewell C (2006) Reduction processes in forest wetlands: tracking down heterogeneity of source/link functions with a combination of methods. *Soil Biology and Biochemistry* **38**, 1028–1039.

Petit S, Firbank L, Wyatt B, Howard D (2001) MIRABEL: models for integrated review and assessment of biodiversity in European landscapes. *Ambio* **30**, 81–88.

Pott R & Remy D (2000) Gewässer des Binnenlandes. Ulmer, Stuttgart.

Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA & Solomon AM (1992) A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate. *Journal of Biogeography* **19**, 117–134.

Prigent C, Papa F, Aires F, Rossow WB & Matthews E (2007) Global inundation dynamics inferred from multiple satellite observations, 1993-2000. *Journal of Geophysical Research* **112**, D12107, doi:10.1029/2006JD007847.

Ramsar Bureau. The Ramsar Convention on Wetlands. Key Documents. Available via : http://www.ramsar.org/index_key_docs.htm.

Ramsar sites (2008) The Ramsar List of Wetlands of International Importance. Gland, Switzerland.

Rebelo L-M, Finlayson CM & Nagabhatla N (2009) Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management* **90**, 2144-2153.

Rodhe A & Seibert J (1999) Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators. *Agricultural and Forest Meteorology* **98-99**, 325-340.

Rooney RC & Bayley SE (2010) Quantifying a stress gradient: An objective approach to variable selection, standardization and weighting in ecosystem assessment. *Ecological Indicators* **10**, 1174-1183.

Rosenqvist A, Finlayson CM, Lowry J & Taylor D (2007) The potential of long wavelength satellite borne radar to support implementation of the Ramsar Wetlands Convention. *Aquatic Conservation: Marine and Freshwater Ecosystems* **17**, 229-244.

Schleupner C (2010) GIS-based estimation of wetland conservation potentials in Europe. In: D Taniar, O Gervasi, B Murgante, E Pardede & B Apduhan (Eds.) Computational Science and Its Applications, Springer, New York, pp. 198-213.

Schleupner C & Schneider UA (2010) Effects of bioenergy policies and targets on European wetland restoration options. *Environmental Science & Policy* 10.1016/j.envsci.2010.07.005.

Schultlink G & Van Vliet R (1997) Wetland identification and protection: North American and European policy Perspectives. Departement of Resource Development. Michigan State University. Available via: http://rdservl.rd.msu.edu/wetlands/ wims/wims_nort.doc.

Schuol J & Abbaspour KC (2006) Calibration and uncertainty issues of a hydrological model (SWAT) applied to West Africa. *Advances in Geoscience* **9**, 137-143.

Silberstein RP (2006) Hydrological models are so good, do we still need data? *Environmental Modelling & Software* **21**, 1340-1352.

Sokolov AP, Schlosser CA, Dutkiewicz S, Paltsev S, Kicklighter DW, Jacoby HD, Prinn RG, Forest CE, Reilly J, Wang C, Felzer B, Sarofim MC, Scott J, Stone PH, Melillo JM & Cohen J (2005) The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation. Report No. 124, Cambridge MA, USA

Stacke T & Hagemann S (2010) The development of a dynamical wetlands extent scheme. *Geophysical Research Abstracts* **12**, EGU2010-10584.

Stillwell-Soller LM, Klinger LF, Pollard D, Thompson SL (1995) The Global Distribution of Freshwater Wetlands. TN-416STR. National Center for Atmospheric Research, Boulder, Colorado. Available via: http://www.scd.ucar.edu/iag/staff/lana/wetlands/.

Strack M (2008) (Ed.) Peatlands and Climate Change. International Peat Society, University of Calgary, Canada

Tiner RW (2009) Global Distribution of Wetlands. University of Massachusetts, Amherst, MA, USA, Elsevier Inc.

Tiner RW (2009b) Wetland hydrology. *Encyclopedia of Inland Waters*, 778-789.

Todd MJ, Muneepeerakul R, Pumo D, Azaele S, Miralles-Wilhelm F, Rinaldo A & Rodriguez-Iturbe I (2010) Hydrological drivers of wetland vegetation community distribution within Everglades National Park, Florida. *Advances in Water Resources*, doi: 10.1016/j.advwatres.2010.04.003.

U.S. Army Corps of Engineers (1997) Wetlands Delineation Manual. Wetlands Research Program Technical Report Y-87-1, Updated version 02/97 including Appendix with Clarifications and Modifications, Washington, DC

Van Diggelen R, Middleton B, Bakker J, Grootjans A & Wassen M (2006) Fens and floodplains of the temperate zone: present status, threats, conservation and restoration. *Applied Vegetation Science* **9**, 157-162.

Van Vuuren DP, Sala OE & Pereira HM (2006) The future of vascular plant diversity under four global scenarios. *Ecology and Society* **11**(2), 25. [online] http://www.ecologyandsociety.org/vol11/iss2/ art25/

Verburg PH, de Koning GHJ, Kok K, Veldkamp A & Bouma J (1999) A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. *Ecological Modelling* **116**, 45–61.

Vervuren PJA, Blom CWPM & De Kroon H (2003) Extreme flooding events on the Rhine and the survival and distribution of riparian plant species. Journal of Ecology **91**, 135–146.

Wagner W, Scipal K, Pathe C, Gerten D, Lucht W & Rudolf B (2003) Evaluation of the agreement between the first global remotetely sensed soil moisture data with model and precipitation data. *Journal of Geophysical Research – Atmospheres* **108** (D19), 4611.

Walter H & Breckle S-W (1991) Ökologie der Erde, Band 1 · Grundlagen. Stuttgart.

Walter BP, Heimann M & Matthews E (2001) Modeling modern methane emissions from natural wetlands 1. Model description and results. *Journal of Geophysical Research* **106**(D24), 34189–34206.

Walton R, Chapman RS & Davis JE (1996) Development and application of the wetlands dynamic water budget model. *Wetlands* **16**, 347-357.

Wang Y (2002) On the modelling of vegetation in earth system/climate models. C^2GCR Report, Montreal, Canada.

Wheeler B (1999) Water and plants in freshwater wetlands. In: RL Wilby & AJ Baird (Eds.) Ecohydrology: plants and water in terrestrial and aquatic environments. Routledge, London, pp 127–180.

Woodward FI, Lomas MR & Betts RA (1998) Vegetation-climate feedbacks in a greenhouse world. *Philosophical Transactions of the Royal Society of London, Ser. B* **353**, 29-38.

Wilby RL, Orr H, Watts G, Battarbee RW, Berry PM, Chadd R, Dugdale SJ, Dunbar MJ, Elliott JA, Extence C, Hannah DM, Holmes N, Johnson AC, Knights B, Milner NJ, Ormerod SJ, Solomon D, Timlett R, Whitehead PJ & Wood PJ (2010) Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. *Science of The Total Environment* **408** (19,1), 4150-4164.

Yu Z, Pollard D & Cheng L (2006) On continental-scale hydrologic simulations with a coupled hydrologic model. *Journal of Hydrology* **331**,110–124.

Zuidhoff FS (2002) Recent decay of a single palsa in relation to weather conditions between 1996 and 2000 in Laivadalen, northern Sweden. *Geografiska Annaler Series A-Physical Geography* **84** A, 103-111.