

University of Groningen

Fens and floodplains of the temperate zone

van Diggelen, Rudy; Middleton, Beth; Bakker, Jan; Grootjans, Ab; Wassen, Martin

Published in:
Applied Vegetation Science

DOI:
[10.1111/j.1654-109X.2006.tb00664.x](https://doi.org/10.1111/j.1654-109X.2006.tb00664.x)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2006

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

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(2), 157-162. <https://doi.org/10.1111/j.1654-109X.2006.tb00664.x>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Fens and floodplains of the temperate zone: Present status, threats, conservation and restoration

van Diggelen, Rudy^{1*}; Middleton, Beth²; Bakker, Jan¹; Grootjans, Ab¹ & Wassen, Martin³

¹Community and Conservation Ecology Group, Biological Sciences, University of Groningen, PO Box 14, 9750 AA Haren, The Netherlands; ²U.S. Geological Survey National Wetlands Research Center, 700 Cajundome Boulevard, Lafayette, LA 70506 USA; ³Copernicus Institute for Sustainable Development and Innovation, Environmental Sciences, Utrecht University, PO Box 80.115, 3508 TC Utrecht, The Netherlands;

*Corresponding author; E-mail r.van.diggelen@rug.nl

Abstract.

This Special Feature focuses on lowland fens and flood plains. In this introduction we discuss the most important mire-related terms, present status, threats and conservation and restoration attempts. Floodplains and especially lowland fens are rare and vulnerable ecosystems. They are highly threatened all over the world because of direct conversion to agricultural land and especially the lack of appropriate management and altered catchment hydrology. Finally we present a framework for the conservation and restoration of these ecosystems. This consists of (1) optimising abiotic conditions; (2) safeguarding propagule availability of the target species; (3) creating and maintaining conditions for (re)establishment of these species, and (4) appropriate management to keep the conditions suitable.

Keywords: Biodiversity; Diversity; River floodplain; Species richness; Water table; Wetland.

Introduction

The present volume contains 16 papers on the analysis, management and restoration of riparian wetlands and lowland fens, 14 of which were presented at the 7th INTECOL international wetlands conference, held from 25-30 July 2004 in Utrecht, The Netherlands. The theme fits the growing recognition of the value of wetland ecosystems worldwide.

The importance of river floodplains as spawning grounds for fish and as productive pasture for domestic cattle is recognised since long by local people. Still, the general attitude of marshes being wastelands comes to expression in wetland-related words such as 'swamp' and 'mud' which definitely have negative connotations in most languages. However, this attitude started to change in the 1960s and 1970s. People began to realise that these ecosystems did possess important values that could be expressed even in economic terms (Pearce 1993; Costanza et al. 1997; van den Berg et al. 2004).

Recently the biodiversity value of certain wetland

types was recognised. Wetlands contain a large number of adapted organisms (Mitch & Gosselink 2000) and, for instance, calcareous fens are among the most species-rich ecosystems of the temperate zone which also harbour many endangered species (Wassen et al. 2005). In addition to biodiversity there are other reasons why wetlands are important. Mires play an important role in the world's carbon balance. Accumulating mires store several 10 000s of kg C per ha per year (e.g. Asada et al. 2005), whereas drained mires lose even larger amounts of CO₂ (Wösten 1997) and other greenhouse gases (Flessa et al. 1998; Groffmann et al. 2002). The role that wetlands play in the purification of water (Olde Venterink et al. 2006, this issue) and in dampening the effect of a large variation in precipitation (Bragg & Lindsay 2003) is important in many places, especially low-lying areas. Wetlands also provide resources such as game, fish, reed and wood (Bragg & Lindsay 2003).

Terminology and definitions

In the literature on wetland ecology there is much confusion about terminology and especially about the distinction between wetland, mire, fen, fen meadows and similar terms. This calls for a section with definitions on how we use some of these terms in this issue.

'Wetlands' are defined as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres' (*Convention on Wetlands in Ramsar, Iran, 1971*).

There are essentially two schools of thought with respect to the definition of mires. The first one states that a 'mire' is a peatland together with peat communities (Godwin 1941), sometimes called a peat-producing ecosystem (Godwin 1956; Gore 1983; Joosten & Clarke 2002) or an area that supports at least some vegetation known to form peat, and usually includes a peat

deposit (Bragg & Lindsay 2003). The second view includes also some non-peat-producing ecosystems such as groundwater-fed calcareous fens (Ratcliffe 1964; Mörsjö 1969) where the main deposit consists of tufa. We follow Joosten & Clarke (2002) and use the word mire in a strict sense for peat producing ecosystems.

Mires can be subdivided into bogs, fens and floodplain mires. The definition of '*bog*' has always been straightforward: a bog is a mire system that is entirely dependent on precipitation for its water and solutes (Du Rietz 1954).

There is more uncertainty about the definition of fen. Originally this term was simply used to describe those types of mires which are not bogs (Du Rietz 1954). Soon people felt the need to make a distinction between poor fens and rich fens, mainly based on vegetation composition. Wheeler (1988) included similar vegetation types on mineral soils also in the definition, whereas Wheeler & Proctor (2000) used pH – and also productivity to some degree – as criteria. All mires with a pH > 5.5 were defined as '*fens*'. Recently there has been a tendency to narrow the definition of fen to ground-water fed wetlands (Bedford & Godwin 2003). We agree with this approach and use the word fen to mean all mires that are pre-dominantly fed by groundwater. Note that wooded wetlands (sometimes called '*carr*') are included in this definition of fen.

The third type of mire is a floodplain, sometimes also called '*flood mire*' (Succow & Joosten 2001). We define a '*floodplain*' as a mire that is predominantly fed by surface water. This definition includes the tall sedge fens and reed swamps from the European literature (e.g. Wheeler & Proctor 2000) and most of the sedge meadows from the American literature (Curtis 1959). These communities are open wetlands dominated by sedges and grasses, and consist mainly of tussocks of large helophytes.

The semi-natural communities '*fen meadows*' and '*wet grasslands*' have developed after human manipulation with water tables. Fen meadows have usually developed from undrained fens after a modest lowering of the water table to increase productivity. Wet grasslands is a more general term that could include fen meadows, but in a strict sense is used to describe managed (drained) floodplains.

Distribution and present status

At present there are no exact data available on the distribution and status of temperate fens and floodplains. Nevertheless some rough figures exist. Lappalainen (1997) and co-authors estimated that an area of slightly less than 4 million km² of mires exist throughout the entire world and another 2.5 million km² for other wetlands. The great majority of these peat deposits are found in the northern hemisphere, especially in the boreal zone, and consist mainly of bogs. The sparse data available suggest that bogs cover a much larger surface area than do fens, which also occur in most countries of the temperate zone. A study by Bragg & Lindsay (2003), however, shows the opposite to be true in eight countries in central-eastern Europe. Here, the majority of the mires consist of fens with 78% of a total of ca. 73 000 km² (5% of the total surface of these countries). The authors estimate that 43% of this surface is still in a nearly natural state.

The situation in North America is rather similar to Europe. The great majority of mires consists of bogs, and fens are mainly found in localized areas with groundwater outflow. In the United States, these areas are found especially in the glaciated Midwest and Northeast, as well as portions of the Appalachian Mountains and mountainous West (Bedford & Godwin 2003). Only fragmented information exists on the present state, e.g. Pearson & Loeschke (1992) estimated that approximately 40% of the fens in Iowa were lost. Bedford & Godwin (2003) wrote: "Few estimates of loss and current extent exist, but where estimates are available, they indicate extensive loss, fragmentation, and degradation".

Changes in the status

Direct conversion

Probably the most important factor affecting fens and floodplains is their conversion into agricultural fields. These wetlands were drained from medieval times onwards and used for grazing cattle and making hay. In the 20th century, drainage technology developed to such a level that even crop production became possible on these wet soils, especially (but not only) in former communist countries. This conversion has resulted in substantial emissions of carbon dioxide and other greenhouse gases, making peat drainage a significant contributor to global warming (Flessa et al. 1998; Groffman et al. 2002).

Compared to bogs, fens are less often used for fuel extraction, but the absolute surface used for this purpose is probably a large threat, especially in somewhat more southern regions where bog peat is rare. The total surface affected is unknown, not in the least because this type

of peat extraction is not well-administered and mostly carried out in small-scale excavations by one-man companies. In bogs, large companies do most of the digging.

Effects of hydrological changes

Fens are especially sensitive to relatively small changes in the hydrological system. Human activities such as groundwater abstraction, large-scale drainage of the surroundings for agricultural purposes and use of groundwater for irrigation lead to a diminished groundwater flow to the fen, even when conducted at large distances from the fen. The effects of groundwater abstraction may often not be visible in the water table inside the fen, but it always leads to an increase in the relative importance of rainwater and finally to acidification of the top layer (Wassen et al. 1996; van Diggelen 1998; Grootjans et al. 2006, this issue). This process may take many decades (van Diggelen et al. 1996; van der Hoek & Šýkora 2006, this issue) and go unnoticed for a while (van Belle et al. 2006, this issue). The factors that control the acidification rate are not completely understood yet, but the speed certainly depends on the amount of acid produced (Kooijman & Paulissen 2006, this issue) and the buffering capacity of the soil (van Diggelen 1998; van Bremen & Buurman 2002).

Water tables in fens and floodplains are lowered due to the more intensive drainage pressure, and this leads to increased mineralisation rates. Most often increased mineralisation rates result in higher biomass production, but they may also lead to a shift in the limiting nutrient (Wassen & Olde Venterink 2006, this issue; Higgins et al. 2006, this issue; van Belle et al. 2006, this issue). Productivity gradients and vegetation patterns change accordingly, in response to altered competition intensity for nutrients and light (Kotowski et al. 2006, this issue).

The opposite situation as to water tables may occur as well, although less often; fens and especially flood-plains sometimes become wetter because of changing water regimes, building of dams and similar activities. Under such conditions, the surface water component increases and nutrient dynamics change, depending on water chemistry and sediment load. Sedimentation is normally the most important nutrient source in floodplains (Olde Venterink et al. 2006, this issue), and increased sedimentation leads to higher nutrient availability (Werner & Zedler 2002) and affects vegetation patterns through shifts in competitive interactions (Kotowski et al. 2006, this issue). However, sedimentation rates vary greatly between vegetation types with different structure (Olde Venterink et al. 2006, this issue).

Conservation and restoration

Fens and floodplains are among the most species-rich habitats but at the same time biodiversity decline has been more intense in these areas than in many other ecosystems. Conservation of existing fens and floodplains and restoration of degraded ones, therefore, is a high priority (Resolution VII.17 of the San José Conference 7th Meeting of the Conference of the Contracting Parties to the Convention on Wetlands (Ramsar), 10-18 May 1999; Final Resolution Adopted at the 7th INTECOL International Wetlands Conference, 25-30 July, 2004). Van Diggelen & Marrs (2003) categorized essential steps for conservation and restoration into four groups:

1. Establishing or re-establishing the necessary abiotic conditions;
2. Supplying (sufficient) propagules of constituent species of the target communities;
3. Creating and maintaining suitable conditions for the (re-)establishment of target species;
4. Appropriate management to keep the conditions suitable.

Establishing and safeguarding necessary abiotic conditions in affected wetlands almost always involves raising the water table (Timmermann et al. 2006, this issue), (re-)establishing the major water source (rainwater, groundwater and surface water) for the wetland under consideration and creating the necessary productivity level regime (van Belle et al. 2006, this issue). Rewetting is in itself technically not so difficult to achieve (Timmermann et al. 2006, this issue; Bodegom et al. 2006, this issue), but conserving and/or restoring the two other parameters may be much more difficult.

Restoration is comparatively easy in floodplains, especially along the edges of water bodies such as larger rivers and lakes where the appropriate water type is nearby. The productivity of the typical vegetation is high, and this makes floodplain vegetation much less sensitive to increased nutrient availability in water and air than are low-production communities (Verhagen & van Diggelen 2006). In the case of fens, it is much more difficult and often impossible to conserve the necessary groundwater feeding. The hydrology of the surrounding landscape has often completely changed (Barendregt et al. 1995; Grootjans et al. 2006, this issue), and groundwater is replaced by rain or surface water. Critical parameters such as productivity, limiting nutrient, light penetration and pH shift outside the limits typical/necessary for fen vegetation, and the characteristic species disappear (van Bodegom et al. 2006, this issue).

Even if the critical abiotic constraints lie within the tolerance of the target vegetation, this vegetation will not necessarily contain all target species, nor will they quickly reappear. Many species do not form a long-

persistent seed bank and have to rely on dispersal to reach a site after local extinction. Other authors (e.g. Novak & Prach 2003; Galatowitsch 2006, this issue) found a clear relationship between immigration rate and isolation of a site, which suggests that dispersal is a constraint for many species. There are also differences between modes of dispersal. Soons (2006, this issue) showed that wind dispersal is of limited value for most wetlands and is negatively affected by increased productivity. Dispersal by water (in flooded parts) and by large herbivores (in grazed parts) seem to be more efficient dispersal vectors (van den Broek et al. 2005; Middleton et al. 2006a, this issue). Of course the latter implies that sites must be connected to each other by a water course or by moving animals.

Species establishment after restoration, (or, in the case of annuals, yearly establishment) is a process that shows many similarities to that of alien species that have to establish in existing vegetation. Presently, we are not able to predict which species will re-establish, and whether or not these species will be invasive. Nevertheless, we do know some of the constraints for establishment. Kotowski et al. (2006, this issue) showed that competition for light was the major factor that kept many species out of the high-productive zone, whereas Bartha et al. (2003) showed that colonisation rates increased significantly after extreme weather events when total species cover had decreased considerably. Chirino et al. (2006, this issue), on the other hand, showed that the relative establishment success was independent from weather conditions but did depend on species identity. All these results suggest that interspecific competition is a major bottleneck for establishment.

Unlike the term 'natural area' suggests, most fens and floodplains are not capable of surviving without regular human intervention. We know from palynological evidence (e.g. van Diggelen et al. 1991; Succow & Joosten 2001; Grootjans et al. 2006, this issue) that large surfaces of base-rich fens were present in natural landscapes at one time. We know also that all over Europe the remaining 'natural fens' are in fact 'fen meadows' that were slightly drained (Wassen & Joosten 1996) and used for hay production and sometimes grazing. The same was true in North America, except that grazing was much more common there than it was in Europe. These activities declined in the second half of the 20th century, and the effects were the same in both continents: shrubs and large helophytes started to invade the sites and gradually took over, outcompeting the original fen vegetation with many light-demanding species (Kotowski et al. 2006, this issue). The situation is much less dramatic in the more productive floodplains, but abandonment also leads to shrub invasion in these areas (Jensen 1998).

Nature management tries to counteract these unwanted developments by applying certain management techniques that mimic traditional agricultural management. The objective of all techniques is to remove excessive nutrients and create recruitment gaps for low-competitive species. The techniques used include mowing and removing hay (Slotte 2001), grazing (Littlewood et al. 2006, this issue) and also burning (Middleton 2002). Apart from many similarities, there are also considerable differences between these techniques (van Diggelen & Marrs 2003; Middleton et al. 2006b, this issue). Mowing creates a spatially homogeneous situation that is highly heterogeneous in time with high selection pressure on species for exact timing of the life-cycle. Low-intensity grazing, on the other hand, often results in a spatially heterogeneous pattern that is stable in time because herbivores create and maintain intensively used grazing lawns adjacent to hardly used spots (Bakker et al. 1984). There are still many uncertainties about the role of fire in managing fens and floodplains. It is obvious that prescribed burning removes dead vegetation and, at least temporarily, results in an increase of biodiversity but winter fire does not control shrubs.

Although not exhaustive, this introduction should point to many research questions concerning the maintenance and restoration of fen and floodplain biodiversity in the temperate zone. This special issue of *Applied Vegetation Science* is a first attempt.

Acknowledgements. We thank Jarita Davis for editorial comments.

References

- Asada, T., Warner, B.G. & Schiff, S.L. 2005. Effect of shallow flooding on vegetation and carbon pools in boreal peatlands. *Appl. Veg. Sci.* 8: 199-208.
- Bakker, J.P., de Leeuw, J. & van Wieren, S.E. 1984. Micro-patterns in grassland vegetation created and sustained by sheep grazing. *Vegetatio* 55: 153-161.
- Barendregt, A., Wassen, M.J. & Schot, P.P. 1995. Hydrological systems beyond a nature reserve, the major problem in wetland conservation of Naardermeer. *Biol. Conserv.* 72: 393-405.
- Bartha, S., Meiners, S., Pickett, S.T.A. & Cadenasso, M.L. 2003. Plant colonization windows in a mesic old field succession. *Appl. Veg. Sci.* 6: 205-212.
- Bedford, B.L. & Godwin, K.S. 2003. Fens of the United States: distribution, characteristics, and scientific connection versus legal isolation. *Wetlands* 23: 608-629.
- Bragg, O. & Lindsay, R. (eds.) 2003. *Strategy and action plan for mire and peatland conservation in Central Europe*. The Central European Peatland Project (CEPP). Publ. No. 18, Wetlands International, Wageningen, NL.
- Chirino, C., Campeau, S. & Rochefort, L. 2006. *Sphagnum* establishment on bare peat: The importance of climatic variability and *Sphagnum* species richness. *Appl. Veg. Sci.* 9: 285-294.
- Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M. & Norgaard, R. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387: 253-260.
- Curtis, J.T. 1959. *The vegetation of Wisconsin*. University of Wisconsin Press, Madison, WI, US.
- Du Rietz, G.E. 1954. Die Mineralbodenwasserzeigergerne als Grundlage einer natürlichen Zweigliederung der nord- und mitteleuropäischen Moore. *Vegetatio* 5-6: 571-585.
- Flessa, H., Wild, U., Klemisch, M. & Pfadenhauer, J. 1998. Nitrous oxide and methane fluxes from organic soils under agriculture. *Eur. J. Soil Sci.* 49: 327-335.
- Galatowitsch, S. 2006. Restoring prairie pothole wetlands: does the species pool concept offer decision-making guidance for re-vegetation? *Appl. Veg. Sci.* 9: 261-270.
- Godwin, H. 1941. The factors which discriminate marsh, fen, bog and heath. *Chron. Bot.* 6.
- Godwin, H. 1956. *The history of the British Flora*. Cambridge University Press, Cambridge, UK.
- Gore, A.J.P. 1983. *Ecosystems of the World, 4B: Mires, Swamp, Bog, Fen and Moor*. Elsevier, Amsterdam, NL.
- Groffman, P.M., Gold, A.J., Kellogg, D.Q. & Addy, K.L. 2002. Mechanisms, rates and assessment of N₂O production in groundwater, riparian and rivers. In: Van Ham, J., Baede, A.P.M., Guicherit, R. & Williams-Jacobse, J.G.F.M (eds.) *Non-CO₂ greenhouse gases: Scientific understanding, control options and policy aspects*, pp. 159-166. Millpress, Rotterdam, NL.
- Grootjans, A.P., Adema, E.B., Bleuten, W., Joosten, H., Madaras, M. & Janáková, M. 2006. Hydrological landscape settings of base-rich fen mires and fen meadows: an overview. *Appl. Veg. Sci.* 9: 175-184.
- Higgins, T., Collieran, E. & Raine, R. 2006. Transition from P- to N-limited phytoplankton growth in an artificial lake on flooded cutaway peatland in Ireland. *Appl. Veg. Sci.* 9: 223-230.
- Jensen, K. 1998. Species composition of soil seed bank and seed rain of abandoned wet meadows and their relation to aboveground vegetation. *Flora* 193: 345-359.
- Joosten, H. & Clarke, D. 2002. *The wise use of mires and peatlands*. International Mire Conservation Group and International Peat Society, Jyväskylä, FI.
- Kooijman, A.M. & Paulissen, M.P.C.P. 2006. Higher acidification rates in fens with phosphorus enrichment. *Appl. Veg. Sci.* 9: 205-212.
- Kotowski, W., Thörig, W., van Diggelen, R. & Wassen, M.J. 2006. Competition as a factor structuring species zonation in riparian fens – a transplantation experiment. *Appl. Veg. Sci.* 9: 231-240.
- Lappalainen, E. (ed.) 1996. *Global peat resources*. International Peat Society and Geological Survey of Finland. Jyskä, Finland
- Littlewood, N.A., Pakeman, R.J. & Woodin, S.J. 2006. A field assessment of the success of moorland restoration in the rehabilitation of whole plant assemblages. *Appl. Veg. Sci.* 9: 295-306.
- Middleton, B.A. 2002. Winter burning and the reduction of *Cornus sericea* in sedge meadows in southern Wisconsin. *Restor. Ecol.* 10: 1-8.
- Middleton, B., van Diggelen, R. & Jensen, K. 2006a. Seed dispersal in fens. *Appl. Veg. Sci.* 9: 279-284.
- Middleton, B.A., Holsten, B. & van Diggelen, R. 2006b. Biodiversity management of fens and fen meadows by grazing, cutting and burning. *Appl. Veg. Sci.* 9: 307-316.
- Mitch, W.J. & Gosselink, J.G. 2000. *Wetlands*. 3rd ed. Chichester, New York, NY, US.
- Mörnsjö, T. 1969. Studies on vegetation and development of a peatland in Scania, South Sweden. *Opera Bot.* 24: 1-187.
- Novák, J. & Prach, K. 2003. Vegetation succession in basalt quarries: Pattern on a landscape scale. *Appl. Veg. Sci.* 6: 111-116.
- Olde Venterink, H., Vermaat, J.E., Pronk, M., Wiegman, F., van der Lee, G.E.M., van den Hoorn, M.W., Higler, M.(L.) W.G. & Verhoeven, J.T.A. 2006. Importance of sediment deposition and denitrification for nutrient retention in floodplain wetlands. *Appl. Veg. Sci.* 9: 163-174.
- Pearce, D.W. 1993. *Economic values and the natural world*. Earthscan, London, UK.
- Pearson, J.A. & Loeschke, M.J. 1992. Floristic composition and conservation status of fens in Iowa. *J. Iowa Acad. Sci.* 99: 41-52.
- Ratcliffe, D.A. 1964. Mires and bogs. In: Burnett, J.H. (ed.) *The vegetation of Scotland*, pp. 426-478. Oliver & Boyd, Edinburgh, UK.
- Slotte, H. 2001. Harvesting of leaf-hay shaped the Swedish landscape. *Landscape Ecol.* 16: 691-702.
- Soons, M.B. 2006. Wind dispersal in freshwater wetlands: Knowledge for conservation and restoration. *Appl. Veg. Sci.* 9: 271-278.
- Succow, M. & Joosten, H. 2001. *Landschaftsökologische Moorkunde*, 2. Aufl. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, DE.

- Timmermann, T., Margóczy, K., Takács, G. & Vegelin, K. 2006. Restoration of peat-forming vegetation by rewetting species-poor fen grasslands. *Appl. Veg. Sci.* 9: 241-250.
- van Belle, J., Barendregt, A., Schot, P. & Wassen, M. J. 2006. The effects of groundwater discharge, mowing and eutrophication on fen vegetation evaluated over half a century. *Appl. Veg. Sci.* 9: 195-204.
- van Bodegom, P.M., Grootjans, A.P., Sorrell, B.K., Bekker, R.M., Bakker, C. & Ozinga, W.A. 2006. Plant traits in response to raising groundwater levels in wetland restoration: evidence from three case studies. *Appl. Veg. Sci.* 9: 251-260.
- van Breemen, N. & Buurman, P. 2002. *Soil formation*, 2nd ed. Kluwer Acad. Publishers, Dordrecht, NL.
- van den Berg, J.C.J.M., Barendregt, A. & Gilbert, A.J. 2004. *Spatial ecological-economic analysis for wetland management*. Cambridge University Press, Cambridge, UK.
- van den Broek, T., van Diggelen, R. & Bobbink, R. 2005. Variation in seed buoyancy of species in wetland ecosystems with different flooding dynamics. *J. Veg. Sci.* 16: 579-586.
- van der Hoek, D. & Sýkora, K.V. 2006. Fen-meadow succession in relation to spatial and temporal differences in hydrological and soil conditions. *Appl. Veg. Sci.* 9: 185-194.
- van Diggelen, R., 1998. *Moving gradients*. Ph.D. Thesis University of Groningen, Groningen, NL.
- van Diggelen, R. & Marrs, R.H. 2003. Restoring plant communities – Introduction. *Appl. Veg. Sci.* 6: 105-110.
- van Diggelen, R., Molenaar, W., Casparie, W.A. & Grootjans, A.P. 1991. Paläoökologische Untersuchungen als Hilfe in der Landschaftsanalyse im Gorecht-Gebiet (Niederlande). *Telma* 21: 57-73.
- van Diggelen, R., Molenaar, W.J. & Kooijman, A.M. 1996. Vegetation succession in a floating mire in relation to management and hydrology. *J. Veg. Sci.* 7: 809-820.
- Verhagen, R. & van Diggelen, R. 2006. Spatial variation in atmospheric nitrogen deposition on low canopy vegetation. *Environ. Pollut.* 144: 826-832.
- Wassen, M.J. & Joosten, J.H.J. 1996. In search of a hydrological explanation for vegetation changes along a fen gradient in the Biebrza Upper Basin (Poland). *Vegetatio* 124: 191-209.
- Wassen, M.J. & Olde Venterink, H. 2006. Comparison of nitrogen and phosphorus fluxes in some European fens and floodplains. *Appl. Veg. Sci.* 9: 213-222.
- Wassen, M.J., van Diggelen, R., Wolejko, L. & Verhoeven, J.T.A. 1996. A comparison of fens in natural and artificial landscapes. *Vegetatio* 126: 5-26.
- Wassen, M.J., Olde Venterink, H., Lapshina, E.D. & Tanneberger, F. 2005. Endangered plants persist under phosphorus limitation. *Nature* 437: 547-550.
- Werner, K.J. & Zedler, J.B. 2002. How sedge meadow soils, microtopography, and vegetation respond to sedimentation. *Wetlands* 22: 451-466.
- Wheeler, B.D. 1988. Species richness, species rarity and conservation evaluation of rich-fen vegetation in Lowland England and Wales. *J. Appl. Ecol.* 25: 331-353.
- Wheeler, B.D. & Proctor, M.C.F. 2000. Ecological gradients, subdivisions and terminology of north-west European Mires. *J. Ecol.* 88: 187-203.
- Wösten, J.H.M., Ismail, A.B. & Van Wijk, A.L.M. 1997. Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma* 78: 25-36.