EFFECTS OF MANAGEMENT AND GROUNDWATER FLUCTUATIONS ON NUTRIENTS AVAILABILITY IN TWO PHOSPHORUS-LIMITED RICH FENS

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Abstract: The most commonly measures to restore rich fens are the reduction of nutrient availability, by means of mowing and hay removal, peat removal and/or grazing, and rewetting. The successful of these measures differs between fens especially between natural and artificial ecosystems. The use of natural fens gradients, which vary systematically in biotic and abiotic factors, is an invaluable tool for understanding mechanism of abiotic control on ecosystem processes. We demonstrate the impact of artificial and natural hydrology on rich fens by comparing to case areas: Upper Basin of the Biebrza valley (natural rich fen) and the Buitengoor (anthropogenic rich fen, the fen is fed by alkaline water coming from an irrigation canal). We found that the relations between specific water types and species composition in this artificial fen are quite similar to those found in the natural rich fen at the Biebrza transect. The occurrence of a number of rich-species is correlated with calcium and alkalinity in both fens. The low productivity in both fens was maintained by a very low P-availability. In the Buitengoor the P-availability was primarily reduced by aluminium and iron, while in the Biebrza rich-fen the calcium rich groundwater was the important sink of phosphorus. Lowering of groundwater and further the invasion of productive species are the most degradation factors in both rich-fens. The conservation of such rich fens by maintaining the natural groundwater flow, mowing and top-peat removal is discussed.

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INTRODUCTION

Fens can be classified by the occurrence of different nutrients (Verhoeven *et al.,* 1983, Koerselman & Verhoeven, 1992), and can be divided in rich or poor fen (Vitt *et al*., 1990). The quantity of these nutrients is depended on the nutrient in- and output, and the nutrient dynamics in the ecosystem, while the nutrient availability is depended on different abiotic parameters. When the availability is low, low productive, but species rich fen communities exist by competition.

The question of which nutrient(s) limit(s) plant growth and productivity in wetlands is still open. Though many freshwater wetlands appear to be N limited, phosphorus (P) limitation can occur in fens with high inputs of aluminium- or calcium-rich waters (Richardson and Marshall, 1986, Boyer and Wheeler, 1989, Wassen *et al*., 1995, Boeye *et al*., 1995, El Kahloun *et al*., 2004), and in N-enriched fens where annual mowing depletes soil P relative to N (Verhoeven and Schmitz, 1991, Wassen *et al*., 1995).

In natural ecosystems rich fens are characterised as receiving a significant groundwater component that rich in base cations (principally calcium, but also magnesium and potassium) but poor nutrients (nitrogen and phosphorus). The bases cations are carried into the fen as groundwater travels over calcareous bedrock such as limestone; therefore, these fens are restricted to areas with significant calcareous geologic deposits. Because of the high concentration of cations, the pH is high, ranging from 6 to 8.5. The rich fens can also be created artificially or changed by human-related activities. Many of these activities are associated with flood irrigation, and other agricultural practices. Examples of artificial wetlands include seeps along irrigation canals, constructed ponds, and wetlands created as part of wastewater treatment processes.

Human interference with hydrology is considered one of the most important factors negatively affecting fen vegetation. In fens in many cases the causes of deterioration originate at larger distance from the mire. This is because regional hydrology is the connecting factor between elevated parts of the landscape, where groundwater is recharged and lowland mires and rivers where groundwater discharges.

This review shows that differences in vegetation types and biomass production between and within fens are related to differences in water supply and nutrient limitation. Several papers have been published about the relations between hydrology and vegetation in these two rich fens (Boeye *et al*., 1994, Boeye *et al*., 1999, Wassen *et al*., 1995, Wassen and Jousten, 1996, El Kahloun *et al*., 2000, El Kahloun *et al*., 2003, El Kahloun *et al*., 2005). In the present overview we refer to the results of previous studies with discussion for which factor limits the biomass production in both rich fen and the management's possibilities to stop degradation and succession in this low productive fens.

STUDY AREAS

BUITENGOOR

The Buitengoor is a headwater valley fen situated on the western slope of the Campine plateau in Belgium. It is a depression in the regional slope where groundwater discharges at the surface and it is the headwater basin of a small rivulet, the fleminkloop. A small irrigation canal runs from south to north across the depression, just above the groundwater discharge zones (Figure 1). This canal is fed with water from shipping canals nearby. At the present, the Buitengoor supports low-growing herbaceous rich fen vegetation *Caricion davaillianae* with many calcicoles species. However, the natural Campine environment normally sustains poor fen vegetations or bogs and does not sustains hydrochemical conditions for rich fen. Boeye *et al*. (1995) concluded that area was transformed recently from poor to rich fen by artificial groundwater recharge. Lembrechts and Van Straaten (1982); Boeye *et al*. (1995) found that the calcareous water from the irrigation canal was responsible for the Buitengoor's rich fen character. The most area is covered by pine and alder forest. In the groundwater discharge zones, herbaceous and low shrubs fen vegetation is present.

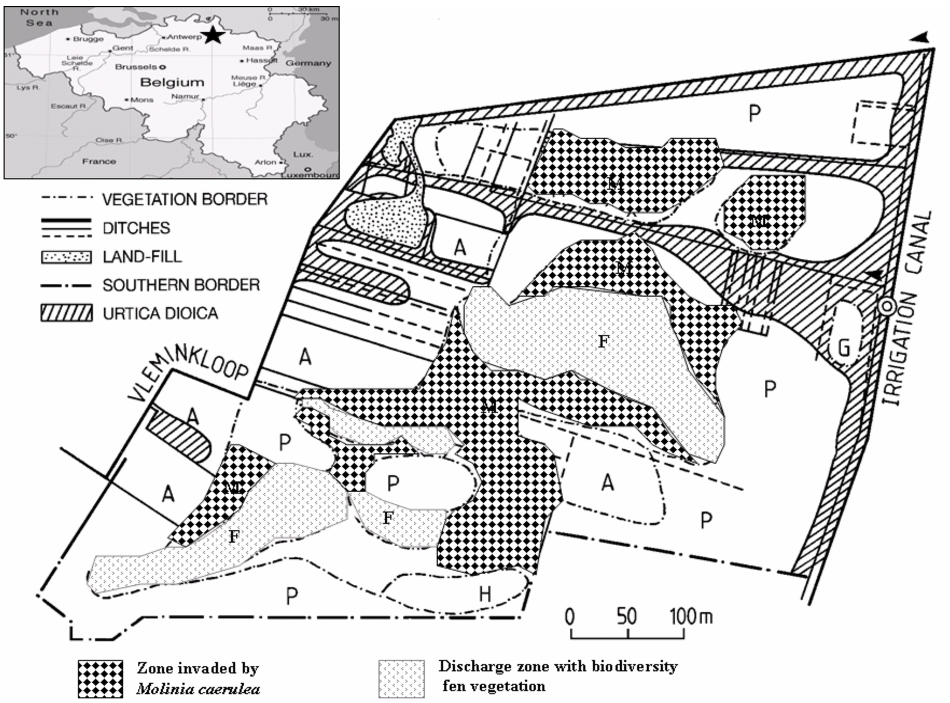

Figure1. * Location of the Buitengoor rich fen in Belgium. F: discharge zones with fen vegetation, M: zones invaded by *M. caerulea,* P: Pinus sylvestris forest. A: Alder forest.

BIEBRZA

The Biebrza valley, situated in north-eastern Poland, is one of the last undrained valleys in Central Europe (Succow and Jeschke, 1986). The catchments are scarcely populated. The Biebrza valley (c. 900 km²) is a protected National Park since 1994. It harbours one of the last and largest examples of undrained fen systems in Europe (Palczynski, 1980; Succow and Jeschke. 1986; Wassen *et al*., 1990a). The valley is divided into three zones, upper, middle and lowers Basin. The relatively narrow upper basin (1-3 km wide) is bordered on the northwest by an outwash plain. In the south, is delimited by a moraine and moraine islands composed of loamy sand and gravel (Wassen *et al*., 1992). The study transect is situated in the upper basin of the Biebrza valley near Lipsk and has a length of 2.3 km (Figure 2). Agricultural influence is minimal, only at the upward part of the transect some very extensive farming occurs on the Lipsk-mineral islands.

GROUNDWATER QUALITY

Piezometers (2.5 m deep, filter in lower 0.5 m) were placed in each sampling station. The piezometers were emptied one day before sampling. Groundwater was sampled from each piezometer. Conductivity and pH of all samples were measured in the field. Concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} and total iron (Fe_t) were determined with inductively coupled plasma-emission spectrometry (ICP). The concentrations of phosphate (PO_4^{3-}-P), nitrate (NO_3^--N), nitrite (NO_2^--N) and ammonium (NH_4^+-N) were measured colorimetrically with a segmented flow (SKLAR auto-analyzer)

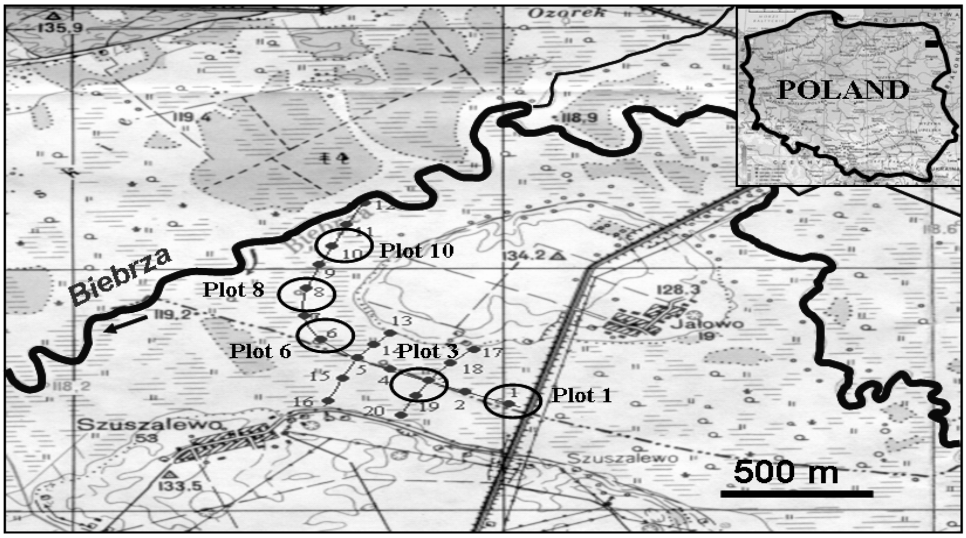

Figure 2. Location of the transect in the Upper Basin of the Biebrza river. Numbers from 1 to 20 indicates piezometers installed in the area, circles indicate the selected piezometers and vegetations plots used for this study.

ABOVE-GROUND BIOMASS

In an earlier study in the Biebrza fen, plant species were recorded in homogeneous plots of 100 m² along transect from the moraine to the Biebrza River and along two laterals transect (El-Kahloun *et al*., 2004)(Figure 2). The height and the cover of the vegetation were estimated, and the abundance was recorded using a five-point abundance scale according to Tansley. Nomenclature for vascular plants follows the Germans flora (Rothmaler, 1994).

In each plot, the above ground vegetation was harvested within 4 randomly chosen quadrants of 0.5 x 0.5 m in June 2002, September 2002, March 2003 and June 2003, separated in living herbaceous plants, moss and litter. After clustering vegetation, we concluded that the vegetation type in the first plots (1 to 4) was characteristic of rich fen. In this paper focuses only on plots 1 and 3.

In the Buitengoor rich fen data of aboveground vegetation were selected from fertilization experiment carried out in the discharge zones of the fen from 1992 to 1998 (El Kahloun *et al*., 2003). Data for biomass production and type of nutrient limitation were reported from the control plots (no nutrient addition) of the fertilization experiment.

For both rich fens aboveground standing crop was dried at 70℃ for 48h, weighted and digested with sulphiric acid peroxide mixture (Houba *et al*., 1989). P- and N-concentrations were determined coloromitetrically (SKALAR auto-analyzer).

STATISTICS

For aboveground compartment of the Biebrza transect, a two-way ANOVA was used to test the effect of location on dead- and living-biomass and nutrient concentrations of aboveground compartment at the end of the growing season. For the Buitengoor results, a two-way ANOVA was used to test the effect of time (from 1992 to 1998) and treatment (nitrogen and phosphorus additions) on the aboveground biomass production and N/P ratio in this aboveground biomass.

RESULTS

GROUNDWATER QUALITY

The Biebrza rich fen was characterized by a calcium-rich groundwater; plot 1 and 3 had the lower calcium-rich groundwater with very low nutrient concentrations (Table 1). The pH was mainly neutral along transect except in the Biebrza River where it was slightly basic. Along the whole transect, going from a tussock forming *C. cespitosa* vegetation near the river, to a moderate rich fen and finally a rich fen further from the river, we found that low ortho-phosphate concentrations in calcareous groundwater support the idea that calcium plays a conditioning role for the vegetation by keeping phosphate availability low. The high base status of the discharge water also maintains a high pH and precludes dissolution of Ca-P oxyhydroxides. While in the Buitengoor, Boeye *et al*., (1995) demonstrated that the alkalinization leads to precipitation of Al-minerals, they concluded that sorption on Al hydroxides is the most important sink of P in the fen.

Table 1. Survey of ground- and surface-water along the transect for sampling periods from 2002 to 2003 (means ± SD) and soil nutrient concentrations.

Water fluctuations	**Groundwater**					**Surface water**
	PLP 1	**PLP 3**	**PLP 6**	**PLP 8**	**PLP 10**	**Biebrza river**
June 2002	-21	-15	-12	-16	-27	
September 2002	-55	-56	-48	-49	-67	
March 2003	-6	-9	2	0	-10	
June 2003	-20	-14	-10	-11	-31	
Water quality	**Groundwater (n=4)**					**Surface water (n=4)**
	PLP 1	**PLP 3**	**PLP 6**	**PLP 8**	**PLP 10**	**Biebrza river**
pH	6.88 ± 0.2	6.95 ± 0.4	7.28 ± 0.1	7.01 ± 0.1	7.01 ± 0.1	7.72 ± 0.1
Conductivity(µs/cm)	407.0 ± 3.6	453.7± 8.4	789.7 ± 24.8	530.3 ± 2.5	603.7±19.8	506 ± 6.2
Na^+ (mg dm^{-3})	4.5 ± 1.2	8.5 ± 8.3	29.4 ± 21.1	12.6 ± 8.6	11.3 ± 0.3	8.5 ± 0.4
K^+ (mg dm^{-3})	1 ± 0.2	0.9 ± 0.1	25.1 ± 2.7	2.4 ± 2.1	5.5 ± 6.9	1.95 ± 0.8
Ca^{2+} (mg dm^{-3})	66.2 ± 0.3	62.4 ± 19.9	101.1 ± 24.8	100.1 ± 29.4	88.3 ± 1.9	79.05 ± 4.6
Mg^{2+} (mg dm^{-3})	12.2 ± 0.5	12.1 ± 0.4	14.9 ± 2.3	16.6 ± 0.9	17.9 ± 0.8	16.15 ± 0.6
Fe^{2+} (mg dm^{-3})	0.5 ± 0.2	0.6 ± 0.4	0.1 ± 0.1	0.3 ± 0.1	5.5 ± 2.3	0.12 ± 0.1
PO_4^{3-}-P (mg dm^{-3})	0.04 ± 0.05	0.02 ± 0.02	0.01 ± 0.0	0.01 ± 0.0	0.02 ± 0.0	0.02 ± 0.0
NO_3^-N+NO_2^--N (mg dm^{-3})	0.04 ± 0.01	0.22 ± 0.3	0.04 ± 0.0	0.04 ± 0.0	0.06 ± 0.0	0.09 ± 0.1
NH_4^+ (mg dm^{-3})-N	0.72 ± 0.3	0.62 ± 0.3	0.55 ± 0.3	0.07 ± 0.0	2.0 ± 0.8	0.05 ± 0.0
Soil Parameter						
	PLP 1	**PLP 3**	**PLP 6**	**PLP 8**	**PLP 10**	
pH (n=4)	6.3 ± 1.0	6.6 ± 0.07	6.9 ± 0.04	6.8 ± 0.20	6.8 ± 0.01	
N (mg N/g dry soil)	21.78	16.61	24.79	37.89	26.20	
P (mg P/g dry soil)	0.58	0.41	0.66	1.07	4.00	
N/P ratio	37.24	40.67	37.39	35.55	6.55	
C/N ratio	19.6	18.5	19.2	14.8	14.4	
Total P in the 30 cm top soil (kg·ha^{-1})	455	238	465	551	3062	

BIOMASS PRODUCTION AND NUTRIENT CONCENTRATIONS

In both rich fens we found very rich-species vegetation, a *Caricion davallianae* vegetation in the anthropogenic Buitengoor rich fen and a *Caricetum limoso-diandrae* in the Biebrza rich fen. This low P availability in groundwater is probably one of the causes of the low productivity found in the study areas. The aboveground biomass production did not exceed 300 g·m^{-2} at the end of the growing season in both rich fens; for the Buitengoor we referred to the control plot (Figure 3 and 4). In general, most P-limited sites are moderate to low productive. Most low productive P-limited or co-limited fens were characterized by a biomass production lower than 650 g·m⁻² (Boeye et al. 1997; Olde Ventrinck et al. 2000; El-Kahloun et al. 2003).

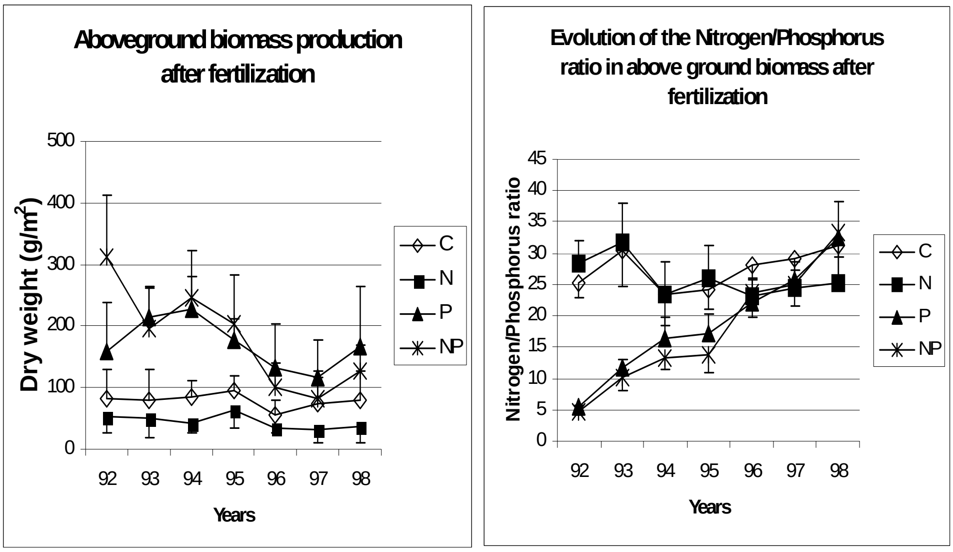

Figure 3. Evolution of aboveground biomass production and Nitrogen/Phosphorus ratio of aboveground biomass seven years after fertilization (from 1992 to 1998) in the Buitengoor-rich fen. Values are means of five replicates. C: Control plot, N: plot fertilized with nitrogen, P: plot fertilized with phosphorus and NP: plot receiving both nitrogen and phosphorus additions.

Fertilization experiments in groundwater discharge zones in the Buitengoor showed an increased aboveground productivity after P addition, while N addition had a negative effect on biomass production. For the aboveground biomass, P was the single most important factor that, seven years after fertilization, continued stimulated growth. N/P ratio of the aboveground vegetation in control (no nutrient addition) indicated a clear phosphorus limitation in the discharges zones of this fen, N/P ratio was all the time higher than 16. In the plots supplied with phosphorus the N/P ratio was very low in the first years and increased progressively to equal values of control seven years after fertilization indicating a re-establishment of P-limited conditions (Figure 3).

In the Biebrza, nutrient concentrations and N/P ratio of aboveground biomass during the peak-growing season indicated a very strong P-limitation along the hole transect, with N/P > 20, except in the zone close to the Biebrza where this N/P ratio decreased significantly to 5 ($p < 0.001$) (Figure 4). The phosphorus content in the peat increases gradually from rich fen with low productive *Caricetum limoso-diandrae* vegetation (455 Kg P.ha^{-1}) to moderate rich fen with *Betuletum humilis*

(551 kg P·ha^{-1}) ending with very high P content in the *C. cespitosa* tussock vegetation, near the Biebrza River (3062 kg P·ha^{-1}) (Table 1).

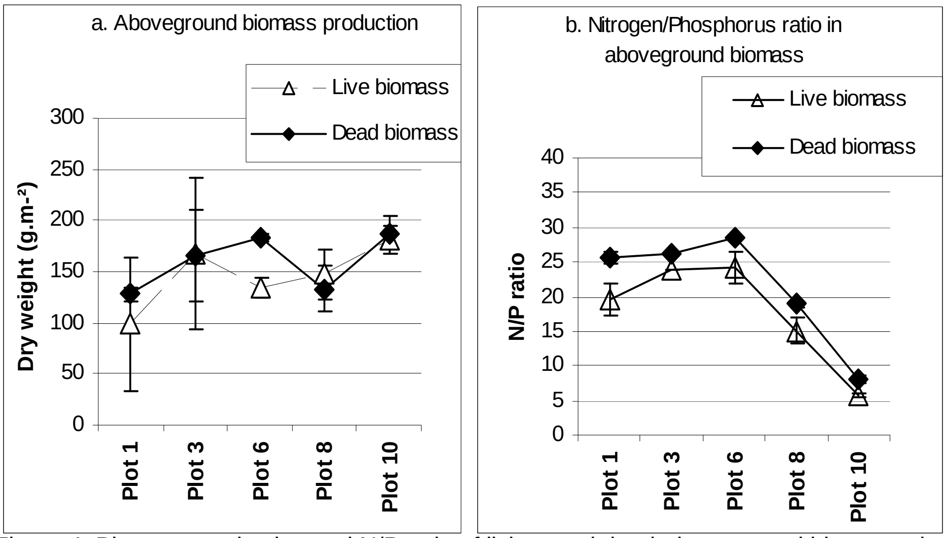

Figure 4. Biomass production and N/P ratio of living- and dead-aboveground biomass along the Biebrza transect at the end of the growing season, September 2002.

DISCUSSION AND CONCLUSIONS FOR THE MANAGEMENT

Factor determining the P-limitation

Like all substances, P availability is a function of its input and output rates to a fen. However, phosphate, the form in which P comes, is a molecule that is easily adsorbed onto precipitated minerals (Fe, Al, Ca, Mg etc.). Therefore fens with exclusive groundwater discharge have often very low P-inputs, as PO_4^{3-} is adsorbed onto aquifer materials. Low mineral P availability in the P-limited rich fen communities seems to be controlled by supply of Calcium and Aluminium rich groundwater. Low soil P-levels are threatened by flooding with high P-waters (external eutrophication) or even by chemical changes of inflowing waters (pH, macro-ionic composition) that interfere with P-precipitating reactions.

This P limitation seems to be controlling factor for the productivity. Olde Venterik (2000) reported that P (co)-limitation was restricted to sites having a biomass less than 650 g m^{-2}. The dry weight of standing crop in the discharge areas was low (< 400 g m^{-2}) in both rich fens (Buitengoor and Biebrza). Concerning species composition, we found in both rich fens, seven species that are included in the red list and are considered as threatened species in the Netherlands and Belgium. Six of these species occurs mostly in phosphorus-limited sites.

PROBLEM OF SUCCESSION AND DEGRADATION

Aerial photos of the Buitengoor show progressive invasion of the low *Caricion davallianae* vegetation by *M. caerulea* tussocks and then after by alder and pine forest (Figure 5). Drier sites are completely closed by *M. caerulea*; while in ground water discharge zones open low growing vegetation persists mixed with small *M. caerulea* tussocks or non-tussock individuals. It appears that in this P-limited conditions *M. caerulea* tussocks set up an efficient retranslocation of P through the roots. The mechanism is also present in non-tussock individuals, where it proved more efficient in the drier areas (El Kahloun et al. 2000).

Fertilization experiments in *M. caerulea*-tussocks show different responses between discharge zones and drier zones. In the drier areas N and P were positively correlated with increases of above-tussock biomass, while in the discharge zones N addition seems to be detrimental. This illustrates the fact that atmospheric deposition can play a crucial role in slowing *M. caerulea*-tussock build up and its dominance in the discharge areas. El Kahloun et al. (2004) report that stable hydrological conditions resulting in permanent flooded areas slow the *M. caerulea* tussock development. From above we can infer that both increased P availability or drier conditions could trigger *M. caerulea* tussock formation. The question treated is now whether a similar mechanism is responsible for the expansion of *C. cespitosa* and *C.diandra*- tussocks in the P-limited rich fen in the Biebrza valley?

In the Biebrza rich fen N/P ratios in above ground plant material found in 2003, revealed that, at the present, the low productive rich fen is strongly P-limited, with N/P-ratio > 20 (El-Kahloun. 2003). However, both growth response and N/P-ratios found in fertilization experiments carried out in 1992 showed that, at that time, all fen types were N-limited (Wassen, 1995). A possible explanation for this shift in limitation could be an increase in external eutrophication. However, from the actual low nutrient concentrations in groundwater, we can infer that no external eutrophication through the groundwater occurs, as did Wassen et al. (1990).
Also, De Mars (1996) reported that atmospheric deposition does not exceed 10 $kg \cdot ha^{-1} \cdot y^{-1}$, which can be considered as very low value. In general, external eutrophication is limited and has not increased since the study of Wassen et al. (1990).
On the other hand, present groundwater levels are lower compared with the levels measured in period from 1987 to 1993 (Wassen et al. 1996). We suggest a lowering of the groundwater table as a possible cause for the change in limitation. Lowering of the groundwater table results in the precipitation of phosphorus, while nitrogen availability increases due to an increase of mineralization. In this P limited conditions certain invasive tussocks-species (especially *C. cespitosa*) are able to increase their P uptake and to expand. Close to the river, increased P availability and/or drier conditions by a decreased groundwater flow could have triggered *C. cespitosa* tussock development. A prerequisite for tussock build up is the set-up of an efficient internal nutrient cycle through a reduced supply of calcium and/or iron

at the root zone, which results in an increased phosphorus availability (El-Kahloun et al. 2004). The development of these invasive tussocks-species can have a negative effect on biodiversity and can stimulate the establishment of trees. Wassen and Okruszko (personal communication) remarked a clear invasion of *Betula pubescens* in the rich fen, the development of these trees may cause lowering of groundwater by increasing evapotranspiration and accelerate the succession to poor fens (Wassen et al. 1992).

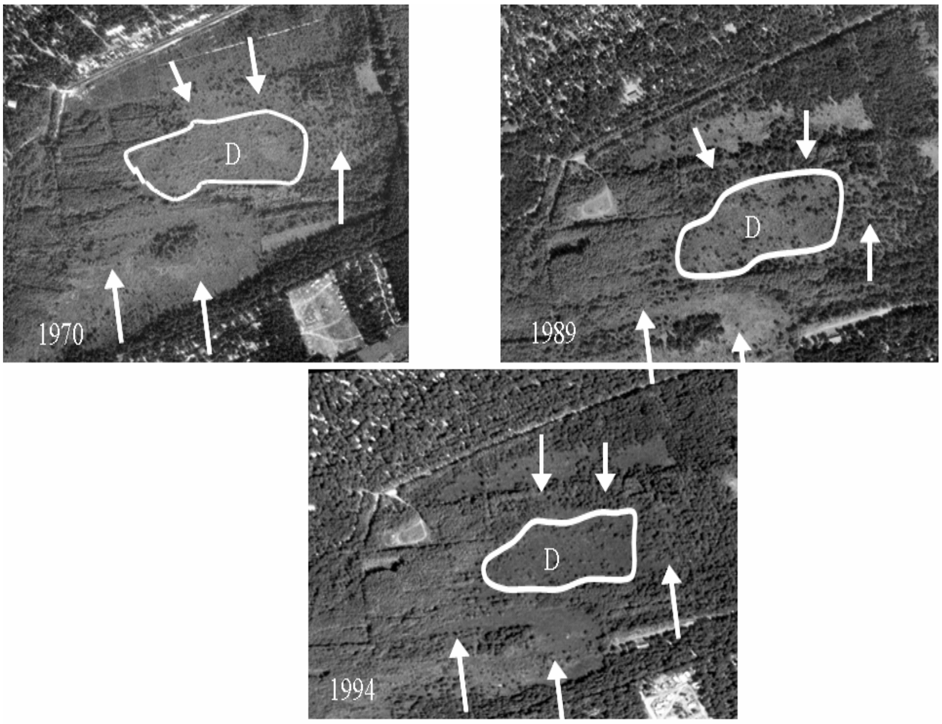

Figure 5. Arial photographs of the Buitengoor showing the evolution of the vegetation from 1970 to 1994. D: discharge zone where the low productive *Caricion davallianae* vegetation still occurs. Arrows shows the closing areas with *M. caerulea* and alder forest.

Groundwater abstraction and climate change result in longer and drier summer can provide conditions for high productive species to increase its nutrient uptake and biomass production. Returning drought conditions allow *M. caerulea* and *C. Cespitosa* to establish big tussocks and reach complete dominance even in discharge zones. Increased decomposition and mineralization by alteration of hydrological conditions often caused dramatic changes in the soil composition initiating succession resulting in establishment of other vegetation types (Moore, 1995).

CONCLUSIONS FOR THE MANAGEMENT

Succession is often considered; as the most important factor for decreasing species richness in fens (Bakker, 1987, Van Duren, 2000, Boeye et al. 1997, El-Kahloun et al. 2003). The *Caricion davallianae* and *Carecetum limoso-diandrae* communities are target communities for conservation and restoration (Wassen et al. 1992, Van Duren, 2000). The restoration and protection differ between and within the fens depending on hydrological conditions and the area of the fens.

Management prescription to protect and to restore the P-limited *Caricion davallianae* communities in the discharges zones should not attempt the total eradication of *M. caerulea*-tussocks by sod-cutting, but should only strive to reduce its dominance. Artificial re-wetting of discharge zones should not be performed because of the risk of P enrichment and a consequent shift from P- to N-limitation. This will induce the disappearance of threatened species (Olde Ventrink, 2000). From our point of view the most effective management may be low intensity summer grazing with light animals or irregular and superficial mowing. These measures should maintain low *M. caerulea* cover and conserve variation in fen species (Hulme et al. 2002; Ross, 2003; Milligan et al. 2004). Management aiming for recolonization of threatened species should focus on establishing a sustainable low P availability by keeping high ground water table. In the Buitengoor some areas in the drier zones were sod cutted in order to decrease P-availability, this step was very successful and we noted establishment of low productive rich fen vegetation and a recolonization of some of threatened species (El Kahloun et al. 2004).

In the Biebrza valley, the large fen area and the limited access render the use of much needed heavy peat removal equipment very costly. Decreasing the drainage in the middle Basin to keep water levels higher and to slow down decomposition and mineralization rates could be effective in preventing further spread of the *C. cespitosa- and C.diandrea*-tussocks vegetation and fast succession to the forest. In 2004 the managers of the Biebrza National Park start cutting *Betula pubescens* trees to keep the area more open. But to stop or slow down the development of the *C. cespitosa* and *C. diandrea*-tussocks, we can conclude that mowing seems to be the adequate and most reasonable management for the Upper Basin.

REFRENCES

Bakker, J.P. 1987. Nature management by grazing and cutting. Kluwer Academic Publishers, Dordrecht.

Berendse, F., Oomes, M.J.M., Altena, H.J. and Elberse W.Th. 1992. Experiments on the restoration of species-rich meadows in the Netherlands. *Biol. Cons*. 62: 59-65.

Boeye, D, Van Straaten, D., Verheyen, R.F. 1995. A recent transformation from poor to rich fen caused by artificial groundwater recharge. *Journal of Hydrology* 169: 111-129.

Boeye, D., Verheyen, R. F. 1994. The relation between vegetation and soil chemistry gradients in a groundwater discharge. *Journal of Vegetation Science* 5: 553 - 560.

Boeye, D., Van Haesebroeck, V., Verhagen, B. and El Kahloun, M. 1999. Phosphorus fertilisation in a phosphorus-limited fen: effect of timing. *Applied Vegetation Science* 2: 71-78.

Boyer, M. L. H., and Wheler, B. D. 1989. Vegetation patterns in spring-fed calcareous fens: calcite precipitation and constraints on fertility. *Journal of Ecology*. 77 : 597 - 609.

De Mars, H. 1993. Soil fertility and nature conservation in Europe: Theoretical considerations and practical management solutions. *Adv. Ecol. Res*. 24: 241-300.

De Mars, H., Wassen, M.J. and Peeters, W.H.M. 1996. The effect of drainage and management on peat chemistry and nutrient deficiency in the former Jegrznia-floodplain (NE Poland). *Vegetatio* 126: 59-72.

El-Kahloun, M., 2004. Vegetation dynamics in P-limited rich fens. PhD Thesis. University of Antwerp.

El-Kahloun, M., Boeye, D., Van Haesebroeck, V., and Verhagen, B. 2003. Differential recovery of above- and below-ground fen vegetation following fertilization. *Journal of Vegetation Science*. 14: 451-458.

El-Kahloun, M., Boeye, D., Verhagen, B. and Van Haesebroek, V., 2000. A comparative study of nutrient status of *Molinia caerulea* and neighboring vegetation in a rich fen**.** *Belgian Journal of Botany*. 133 (1-2): 91-102.

El-Kahloun, M., Gerard, M. and Meire, P. 2005. Phosphorus and Nitrogen cycling in fen vegetation along different trophic conditions in the Biebrza valley, Poland. *Ecohydrology & Hydrobiology*. 5 (1): 68-79.

Grootjans, A.P. and Van Diggelen, R. 1995. Assessing the restoration prospects of degraded fens. In: Wheeler B.D., Shaw S.C., Fojt W.J. and Robertson R.A (eds). Restoration of temperate Wetlands. Wiley and Sons, Chichester. Pp 73-90.

Grough, M.W. and Marrs, R.H. 1990. A comparison of soil fertility between semi-natural and agricultural plant communities: implication for the creation of species-rich grassland on abandoned agricultural land. *Biological Conservation* 51: 83-96.

Houba, V. J.G., Van der Lee, J. J., Novozamsky, I., and Wallinga, I., 1989. - Soil and plant analysis, a series of syllabi. Part 5. Soil analysis procedures. Wageningen, Agricultural University.

Koerselman, W. and Verhoeven, J.T.A. 1992. Nutrient dynamics in mires of various trophic status: nutrient inputs and outputs and their internal nutrient cycle. In: Verhoeven J.T.A. (eds) Fens and Bogs in the Netherlands. Kluwer, Dordrecht. pp 397-432.

Olde Ventrink,H. and Wassen, M.J. 2000. A triaxal NPK diagram to distinguish the type of nutrient limitation in herbaceous wetlands. In: S. Güsewell, J. Verhoeven and W. Koerselman (eds) Nutrient Limitation and Species Diversity of Wet and Dry Herbaceous vegetation. Pp: 5. Workshop Proceeding, Department of Plant Ecology and Evolutionary Biology, Utrecht Unversity.

Palczynski, A. 1980. Succession trends in plant communities of the Biebrza valley. Towards protection and sustainable use of the Biebrza Wetlands: Exchange and integration of research results for the benefit of Polish-Dutch Joint Research Plan. Slected from Workshop" Biebrza Wetlands" October 1993, IMUZ, Falenty: 5-20.

Patrick, W. H. and Khaled R. A., 1974. - Phosphate release and sorption by soil and sediments: Effect of aerobic and anaerobic conditions. *Science* 186 : 53 – 55.

Van Duren, I.C. 2000. Nutrient Limitation in Drained and Rewetted Fen Meadows. PhD Thesis, University of Groningen.

Verhoeven, J.T.A., Van Beek, S., Dekker, M. and Storm, W. 1983. Nutrient dynamics in small mesotrophic fens surrounded by cultivated land. I. Production and nutrient uptake by vegetation in relation to flow of eutrophicated ground water. *Oecologia* 60: 25-33.

Wassen, M.J. 1995. Hydrology, water chemistry and nutrient accumulation in the Biebrza fens and floodplains (Poland). *Wetlands Ecology and Management* vol. 3. 2: 125-137.

Wassen, M.J., Barenbregt, A., Palczynski, A., de Smidt, J.T. and de Mars, H. 1990. The relationship between fen vegetation gradients, groundwater flow and flooding in an undrained valley mire at Biebrza, Poland. *Journal of Ecology* 78: 1106-1122.

Wassen, M.J. Barendregt, A. Palczynski, A. de Smidt, J.T. and De Mars. 1992. Hydro-ecological analysis of the Biebrza mire (Poland). *Wetlands Ecology and Management* 2 (3): 119-134.

Wassen, M.J., Joosten, J.H.J. 1996. In search of hydrological explanation for vegetation changes along a fen gradient in the Biebrza Upper Basin (Poland). *Vegetatio* 124 (2): 191-209.

Vitt, D. H and Chee, W. L. 1990. The relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. *Vegetatio* 89: 87-106.

Richardson, C.J., Marshall, P.E. 1986. Processes controlling movement storage and export of phosphorus in a fen peatland. Ecol. Monographs 65, 279-302.

Verhoeven, J.T.A., and Schmitz, M.B. 1991. Control of plant growth by nitrogen and phosphorus in mesotrophic fens. *Bigeochemistry* 12: 135-148.

Slack, N.G., Vitt, D.H and Horton, D.G. 1980. Vegetation gradient in the north-western part of the province Overijssel (The Netherlands). Wetnia 15: 109-141.