Large Rivers Vol. **15**, No. 1–4
Arch. Hydrobiol. Suppl. 155/1–4, p. 243–260, Mai 2005

Rehabilitation of alluvial landscapes along the River Hase (Ems river basin, Germany)

M. Stroh[1,2], A. Kratochwil[2], D. Remy[2], K. Zimmermann[3] and A. Schwabe[1]

With 6 figures and 4 tables in the text

Abstract: Extensive alluvial pasture landscapes with high biodiversity were for centuries characteristic of the northwestern German lowland plains, but for 50 years nearly all have been replaced by intensive agricultural management systems. As part of a rehabilitation project an alluvial pasture landscape along the River Hase (Ems river basin) was to be redeveloped. The dikes were set back and soil and sand were rearranged, creating a wetland-river dune complex low in nutrients. Hardly any plant species were present in the seed bank. Without any further assistance mainly hydrochoric wetland plant species were expected to colonize the area, whereas anemo- and zoochoric river dune plant species and those of dry grassland growing today only on fragmented sites would not be in a position to reach the rehabilitated area in the near future. Therefore, the areas have been inoculated with diaspores from mown and raked plant material taken from special source areas (Spergulo-Corynephoretum, Diantho-Armerietum). Results after two vegetation periods indicate that the plant species composition at the inoculated plots develop in the desired direction in contrast to non-inoculated plots. A long-term cattle grazing scheme was set up to prevent vegetation succession and guarantee a dynamic system of pioneer communities.

Key words: river dune vegetation, inoculation experiments, winter flooding, redynamization, Spergulo-Corynephoretum, Diantho-Armerietum.

Introduction

In the northwestern German lowland plains nearly all riverine habitats have in recent decades been intensively cultivated with high fertilization input. However, due to decreasing agricultural land use of riverine sites with only marginal yields (Riecken et al. 2001) and the necessity to conserve and to develop endangered (semi-)natural riverine habitats according to the Flora-Fauna-Habitat directive (De

---

Authors' addresses: [1] Darmstadt University of Technology, Vegetation Ecology, Schnittspahnstr. 4, D-64287 Darmstadt, Germany. [2] University of Osnabrück, Ecology, Barbarastr. 11, D-49069 Osnabrück, Germany. [3] Darmstadt University of Technology, Geodesy, Petersenstr. 15, D-64287 Darmstadt, Germany.

0945-3784/05/0155-0243 $ 4.50

Waal et al. 1998; Ssymank et al. 1998), successful rehabilitation methods are becoming more important.

Any restoration or rehabilitation project should explicitly define which goal the intended measures should pursue (Palmer et al. 1997; White & Walker 1997; Bakker et al. 2000; Van Diggelen et al. 2001). As reference landscape we chose an alluvial pasture-woodland vegetation complex, which has already been present for centuries in the Emsland region and is one of the few remaining fragments of this vegetation type (Pott & Hüppe 1991). This ecosystem complex is characterized by a high biodiversity and the occurrence of many endangered plant and animal species (Assmann & Kratochwil 1995; Kratochwil & Assmann 1996).

We expect it will be possible to convert intensively managed maize/cereal fields and pasture areas into an alluvial landscape characterized by wetlands and river dune complexes with high biodiversity. Today, vegetation cover either prevents aeolian sand transport processes or – as in the case of maize fields – is extremely rich in nutrients. Only fluvial sand transport occurs to a lesser extent. Therefore we need to begin by taking landscape architectural steps. Experiments performed in the course of our study proved that the following steps are indispensable for the rehabilitation of alluvial landscapes:

1. Development of the necessary abiotic conditions:
    - Shaping a heterogeneous surface relief (higher dune complexes such as sand accumulations, deeper parts for the establishment of wetland vegetation and ephemeral and permanent water plots).
    - Reduction of nutrients and prevention of ruderalization processes by soil inversion.
    - Facilitating flooding events and river dynamics, so that sandy material will be deposited during winter floods.
2. Development of the necessary biotic conditions:
    - Introduction of diaspores and plant material from areas characterized by target river dune vegetation (Spergulo-Corynephoretum, Diantho-Armerietum).
    - Additionally inoculation of commercial seed mixtures in the low-lying areas with species of more productive pasture vegetation (rich in *Festuca pratensis*) to provide enough phytomass for cattle grazing.

Materials and methods

The rehabilitation project is located on two meanders of the Hase river ("Hammer meander" and "Wester meander") between Haselünne and Meppen (northwestern Germany) (7°26′ east, 52°34′ north). Reference sites are situated in the nature reserve "Sandtrockenrasen am Biener Busch" near Lingen close to the river Ems (7°15' east, 52°34′ north) and near "Hammer meander". The maximum difference between high and low water marks of the river Hase recorded between 1999 and 2003 was 385 cm (winter maximum 403 cm; summer minimum 18 cm) (data from

“Niedersächsischer Landesbetrieb für Wasserwirtschaft und Küstenschutz, Meppen”).

- Planning phase and nutrient analysis (completed by the end of 2000)

Prior to actual rehabilitation, models of the landscape relief were established based on historical data (maps from 1900 and 1990, aerial pictures taken in 1956 and 1995).

The nutrient status (N and P; upper [0–30 cm] and deeper [31–100 cm] soil layer) was analysed in the “Hammer meander” (May 2000): N_{total} using a Kjeldahl apparatus (Gerhardt), and P analyses with a Flow Injection Analyzer (Perkin Elmer). 43 plots were tested within 3 parallel transects SW–NO and one transect N–S (fields n = 13, plot distance 100 m; intensively managed grasslands n = 18, plot distance 100 m; old dunes n = 5, plot distance 10 m; dikes n = 7, plot distance 300 m); 197 mixtures of 350 g (each mixture consisting of 3 samples).

- Rehabilitation of relief structures, seed bank analysis (summer 2001, spring 2002)

On the two meander cores a new relief was shaped and the dikes were set back to initiate natural hydrodynamic processes (Fig. 1). Relief-structures (“neo-dunes”) and temporarily flooded hollows were created (Fig. 2); dike material was used to construct parts of the “neo-dunes”. Upon completion, 67,000 m^3 of soil/sand material had been moved within an area of 37 ha.

Thereafter samples were taken to assess the diaspore reservoir in the soil of the newly created sand accumulations (26 and 27 March 2002). 40 soil samples (mix-

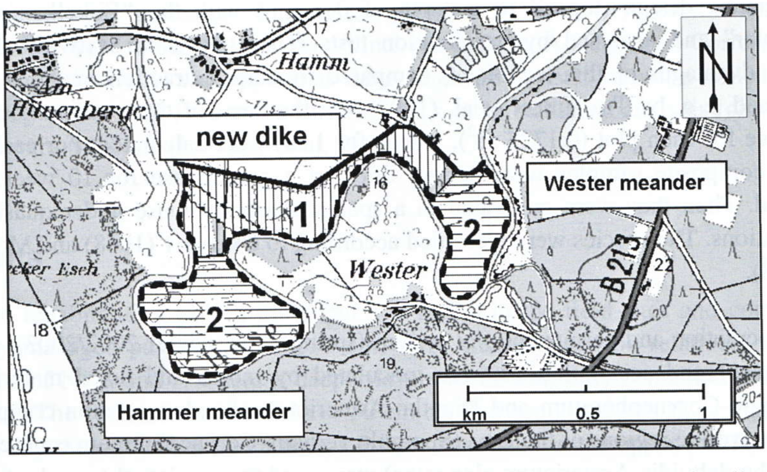

Fig. 1. Total area of rehabilitation (76 ha). 1: maize/cereal field and conventionally managed pasture land south of the new dike; 2: areas of landscape rehabilitation “Hammer meander” and “Wester meander” (37 ha); broken line: old dike.

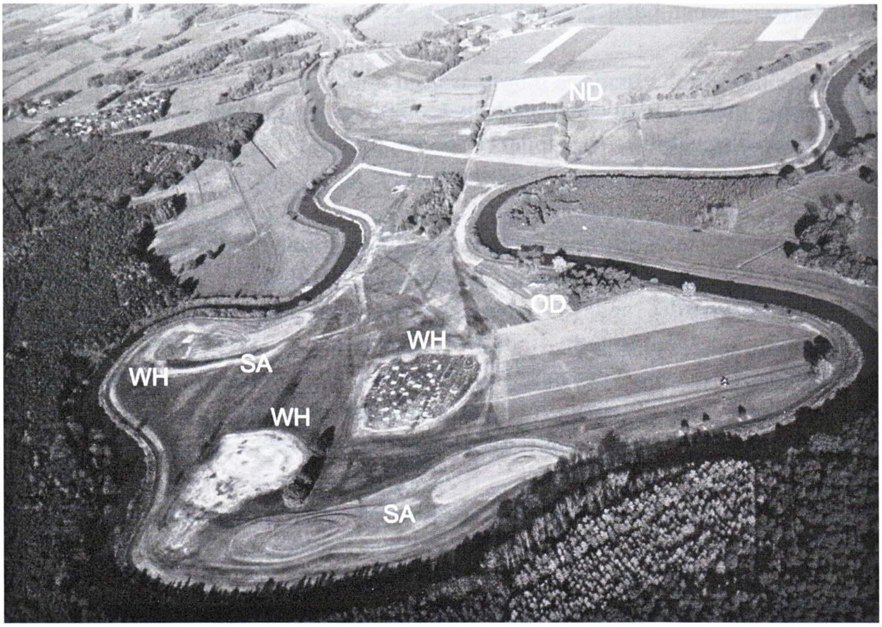

Fig. 2. Aerial photo of the "Hammer meander" after rehabilitation in 2001. ND = new dike; SA = sand accumulations ("neo-dunes"); OD = old dune fragment; WH = water holes (Photo: Mecklenborg).

tures of 400 samples) were extracted from a plot of 25 m^2 according to a random systematic design (topsoil to a depth of 0–6 cm) with the "Eijkelkamp liner sampler" and analysed by germination tests (KROLUPPER & SCHWABE 1998). The advantages of this technique, compared to other extraction methods, were outlined, e. g. by THOMPSON et al. (1997). On the basis of the total sampled soil surface for each plot (0.1725 m^2), values for 1 m^2 were calculated. For each plot area composite samples were sorted, dried in a greenhouse for 10 weeks and sieved. Then they were cultivated in a special diaspore house under quasi-field conditions. The species were identified according to CSAPODY (1968) and MULLER (1978).

– Inoculation and permanent plot system (spring 2002, winter 2002/2003)
The new sand accumulations were inoculated by mown and raked material of Spergulo-Corynephoretum and Diantho-Armerietum. Sand vegetation complexes in the riverine regions of the Ems (Spergulo vernalis-Corynephoretum canescentis, Diantho deltoidis-Armerietum elongatae) were used to inoculate the newly created river dune complexes. 860 kg (fresh weight) of mown and raked material was applied in an area of 960 m^2 (Fig. 2). The reference and donor plots of the

Spergulo-Corynephoretum are situated in the nature reserve "Sandtrockenrasen am Biener Busch", whereas fragments of the Diantho-Armerietum are situated in an area near "Hammer meander". A former field in the nature reserve "Sandtrockenrasen am Biener Busch" (grazed by cattle since 1995) served as an additional reference area (rehabilitation without inoculation of target species).

Low-lying areas (13.7 ha) were inoculated with commercial seed mixtures (plant species of *Festuca pratensis*-grassland; sow mixture N1, "Landesanstalt für Ökologie, Bodenordnung und Forsten Nordrhein-Westfalen", Recklinghausen/Germany; 35 kg/ha).

The vegetation dynamics influenced by abiotic processes and extensive grazing were studied by analyses of permanent plots and a grid-based permanent plot system. Permanent plots with and without grazing were established in the reference areas in the year 2000 (7 plots each, size 25 m^2), 16 plots each in the rehabilitation areas in 2001, the latter were differentiated into non-inoculated and inoculated plots. The relevés were sampled according to BARKMAN et al. (1964). A grid-based permanent plot system for vegetation analyses covered all habitat types of the rehabilitation and reference areas (point distance 50 m). The grid system allowed a regular survey of the vegetation structures (circles of 80 m^2). Plot numbers: nature reserve area "Sandtrockenrasen am Biener Busch" n = 36, "Hammer meander" n = 94, "Wester meander" n = 28.

The geomorphological development was studied with the help of colour-infrared-aerial picture analyses (limit of ground resolution 7 x 7 cm; scale 1:2200–1:2500). The first dynamic processes after removal of the dikes occurred during the floods between December 2001 and March 2002.

– Data analysis

Ordinations were implemented using the program PC-Ord 4.19. BRAUN-BLANQUET scores were transformed to an ordinal scale (0–9). A Detrended Correspondence Analysis (DCA) was applied as the gradient of floristic variation turned out to be long (about 3 SD) (KENT & COKER 1992); other statistical analysis followed the program SAS 8.2 (LITTELL et al. 2000).

Results

Prior to rehabilitation (2000) the upper soil layers in the field sites and conventionally managed pasture land (0–30 cm) were characterized by relatively large amounts of N_{total} and P, whereas deeper layers (> 30 cm) only contained smaller amounts. The cores of the old dikes (> 30 cm depths) contained less N_{total} than the intensively managed sites and also less P than was found in the upper soil layer of the maize/cereal field sites (Table 1); therefore these cores were suitable for the construction of the upper parts of the "neo-dunes".

Infrared aerial pictures illustrate the different situations before and after the

Table 1. P (mg/kg) and N_{total} (%) values of "Hammer meander" (different sites) before rehabilitation measures.

site	P (mg/kg)		N_{total} (%)		plot	sample
depth	0–30 cm	30–60 cm	0–30 cm	30–60 cm	numbers	numbers
field	94.3	29.4	0.054	0.031	13	
SE	10.4	3.5	0.006	0.005		
n	16	28	16	30		90
pasture land	37.0	13.7	0.133	0.044	18	
SE	2.98	2.67	0.019	0.009		
n	19	16	18	22		75
old dune	25.8	13.5	0.042	0.025	5	
SE	2.29	0.70	0.007	0.002		
n	4	5	4	5		18
dike core	–	15.4	–	0.027	7	
SE	–	1.45	–	0.003		
n	–	7	–	7		14
					43	197

rehabilitation. After rehabilitation the alluvial landscape is characterized by a larger geomorphological and biological diversity (Fig. 3, Table 2). After the dikes had been set back in autumn 2001, floods could be observed when the water table exceeded 290 cm. In winter 2001/02 parts were flooded for 26 days, in winter 2002/03 for 17 days. In 2002 (February) and 2003 (January) the water level reached 350 cm for 2 and 4 days, respectively. These flood events scoured channels, and extensive sand plains with typical current ripple marks developed. During one winter fluvial sandy material was deposited on 9 % of the whole rehabilitated area (Table 2). Floods did not overflow the top of the newly created sand accumulations, which were inoculated with plant material from the reference areas.

Immediately after the creation of the new sand accumulations, the diaspore content in the soil was extremely low. 530, 179, 179, 352 diaspores/m^2 were present at four plots, consisting of 31 species (Table 3). Only few ruderal species, e.g. *Chenopodium album*, dominated the seed bank. Less than 0.5 % of the seeds belonged to target species of the Koelerio-Corynephoretea.

→

Fig. 3. Top: infrared photo of the "Hammer meander". Situation before rehabilitation (2001) with maize/cereal fields and conventionally managed pasture land. Bottom: situation after rehabilitation (2003) with a mosaic of extensively grazed pasture land (fresh to moist; dry), sand accumulations ("neo-dunes"), fluvial sand layers and permanent and periodically flooded water holes (numbers refer to Table 2).

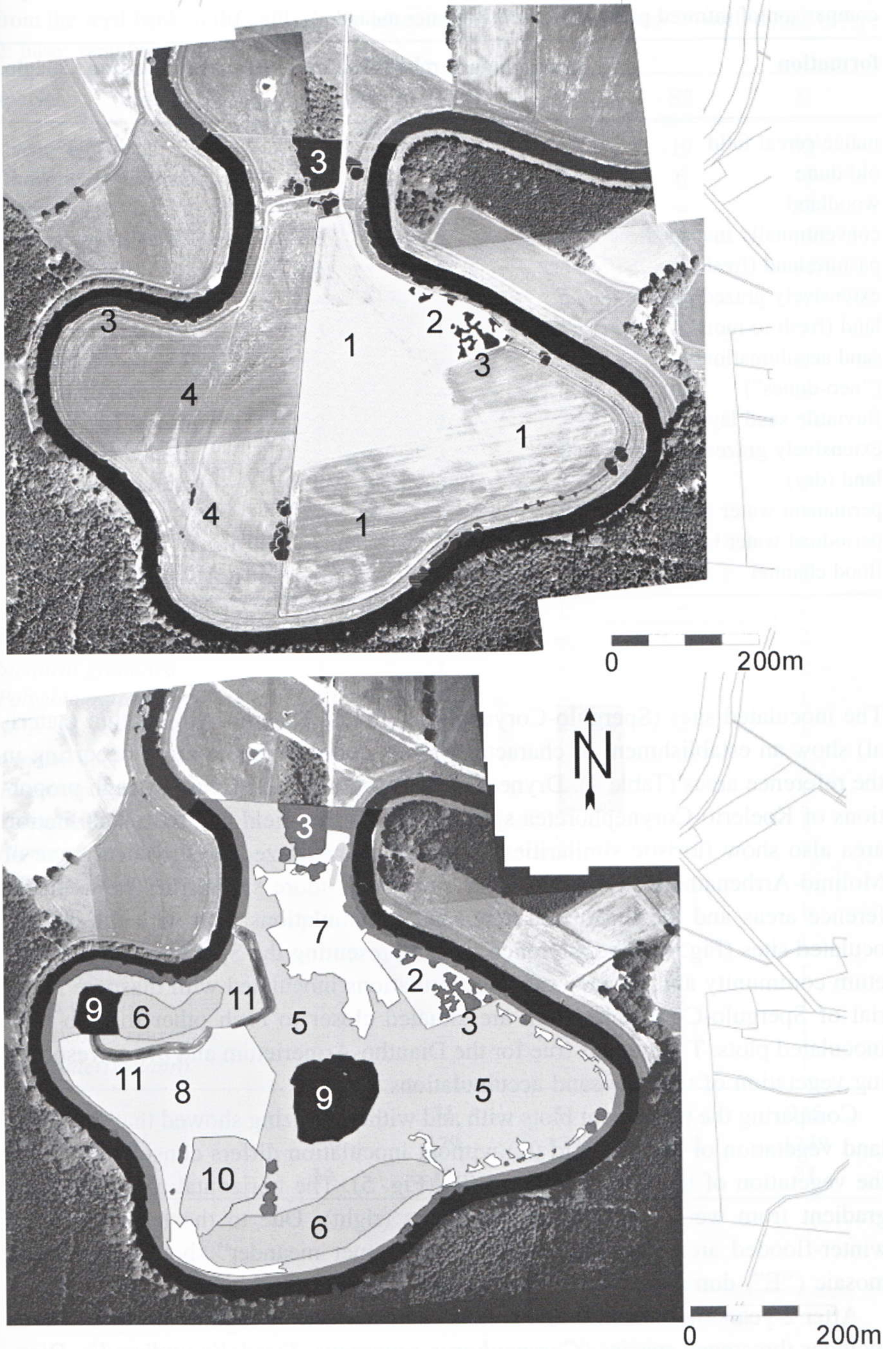
3
3
2
1
3
4
1
4
1
0
200m
N
3
7
2
9
6
11
5
3
11
8
9
5
10
6
0
200m

Table 2. Change of habitat types before and after rehabilitation measures, analysed by a comparison of infrared pictures of the "Hammer meander" (Fig. 3).

formation	code	before rehabilitation (in % of area)	after rehabilitation (in % of area)	origin
maize/cereal field	1	43		man
old dune	2	3	3	wind
woodland	3	5	5	man
conventionally managed pasture land (fresh)	4	49		man
extensively grazed pasture land (fresh to moist)	5		55	man
sand acculumations ("neo-dunes")	6		10	man
fluviatile sand layer	7		9	river
extensively grazed pasture land (dry)	8		7	man
permanent water holes	9		5	man
periodical water holes	10		4	man
flood channel	11		2	river

The inoculated sites (Spergulo-Corynephoretum and Diantho-Armerietum material) show an establishment of character species quite similar to those occurring in the reference areas (Table 4). Dryness of the sites is demonstrated by high proportions of Koelerio-Corynephoretea species. The former field and the rehabilitation area also show floristic similarities. Both are characterized by the occurrence of Molinio-Arrhenatheretea species. There are many more similarities between reference areas and the inoculated new sand accumulations than with the non-inoculated sites (Fig. 4). The reference plots representing the Spergulo-Corynephoretum community and the new sand accumulations inoculated with diaspore material of Spergulo-Corynephoretum are situated closer to each other than to non-inoculated plots. The same is true for the Diantho-Armerietum and the corresponding vegetation of the new sand accumulations.

Comparing the permanent plots with and without grazing showed that the grassland vegetation of the old field (C) without inoculation differs considerably from the vegetation of the reference areas (B) (Fig. 5). The horizontal axis displays a gradient from wet (left) to drier conditions (right). Due to the large extent of winter-flooded areas the habitats in the "Hammer meander" show a vegetation mosaic ("E") dominated by wetland communities.

After 2 years the rehabilitation area is characterized by high diversity and even includes threatened species (*Corynephorus canescens, Teesdalia nudicaulis, Dianthus deltoides, Myosurus minimus*). Inoculated plots have a significantly higher

Table 3. Number of germinated seeds of newly created sand-accumulation sites arising from the seed bank in the soil prior to inoculation; W = west dune; S = south dune; 1: top, 2: base; sampling in spring 2002.

species	**W1**	**W2**	**S1**	**S2**	**Σ**
Juncus bufonius	19	8	6	19	52
Chenopodium album	31	4	5	6	46
Agrostis sp.	18	3	1	–	22
Tanacetum vulgare	6	2	6	1	15
Holcus lanatus	6	5	2	1	14
Digitaria ischaemum	–	–	1	7	8
Artemisia vulgaris	3	1	2	1	7
Gnaphalium uliginosum	–	–	–	6	6
Trifolium dubium	–	–	1	4	5
Agrostis capillaris	2	2	–	1	5
Juncus articulatus	–	3	–	1	4
Leontodon saxatilis	–	–	–	4	4
Solanum nigrum	–	–	–	3	3
Rorippa palustris	–	–	1	2	3
Carex arenaria	–	–	2	–	2
Rumex acetosella	1	–	1	–	2
Echinochloa crus-galli	–	–	–	2	2
Stellaria graminea	1	1	–	–	2
Polygonum hydropiper	1	–	–	–	1
Salix sp.	1	–	–	–	1
Cirsium sp.	1	–	–	–	1
Juncus sp.	1	–	–	–	1
Spergula arvensis	1	–	–	–	1
Plantago lanceolata	–	–	1	–	1
Herniaria glabra	–	–	1	–	1
Veronica sp.	–	–	1	–	1
Corynephorus canescens	–	1	–	–	1
Linaria vulgaris	–	1	–	–	1
Juncus effusus	–	–	–	1	1
Echinochloa crus-galli	–	–	–	1	1
Hypochaeris glabra	–	–	–	1	1
Σ seedlings	**92**	**31**	**31**	**61**	**215**
Σ seedlings/m^2	**530**	**179**	**179**	**352**	**1239**
Σ species	**14**	**11**	**14**	**17**	**31**

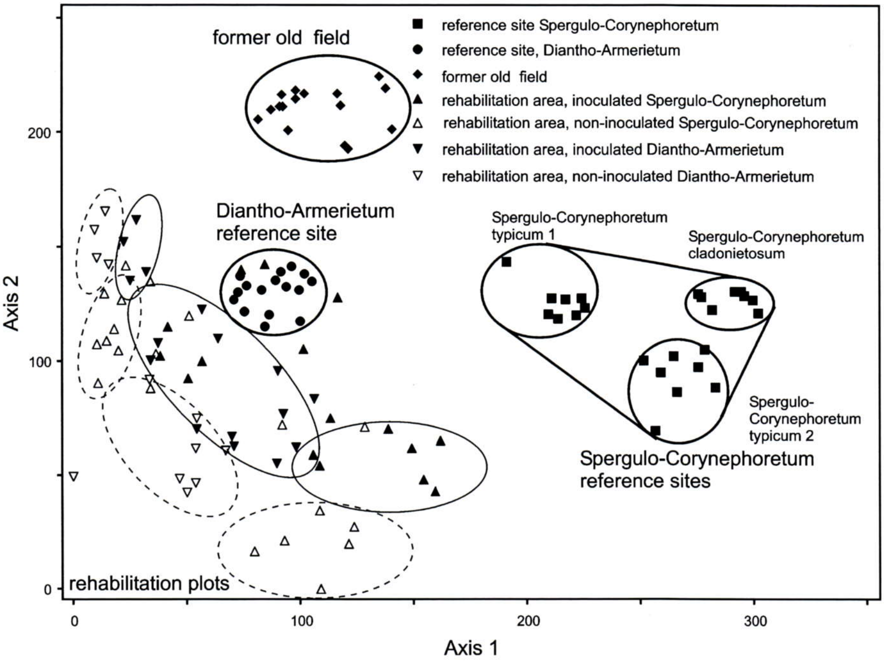

Fig. 4. Detrended Correspondence Analysis (DCA) for permanent vegetation plots with or without grazing in the reference and rehabilitation areas. Dotted outline: non-inoculated plots; thin outline: inoculated plots; thick outline: reference plots. Eigenvalues: axis 1 = 0.43, axis 2 = 0.16 (axis 3 = 0.10).

number of species per plot than non-inoculated plots (Mixed linear model, SAS proc mixed, F = 26.21, Pr [F] > 0.0001) (Fig. 6). In all cases, there are significant differences between non-inoculated and inoculated plots and between plots inoculated with either Spergulo-Corynephoretum or Diantho-Armerietum plant material.

Discussion

The threatened target river dune plant communities (Spergulo-Corynephoretum, Diantho-Armerietum) are restricted to nutrient-poor soil conditions, which guarantee a species diversity typical of the site with the lowest ruderalization effects (GLEMNITZ et al. 1998; CHRISTIANSEN 2000; REMY & MENZEL 2004; STORM & BERGMANN 2004). Therefore, the soil layers rich in N and P (0–30 cm) ("sink habitats", AERTS et al. 1995) had to be transferred into the core of the "neo-dunes" and then covered by nutrient-poor layers lacking diaspores of ruderal plant species. In contrast to nitrogen-rich fields (0.15–0.30 %; OEHMICHEN 1983), the content values (N_{total}) of the new sand surface (0.025–0.027 %) correspond to those of

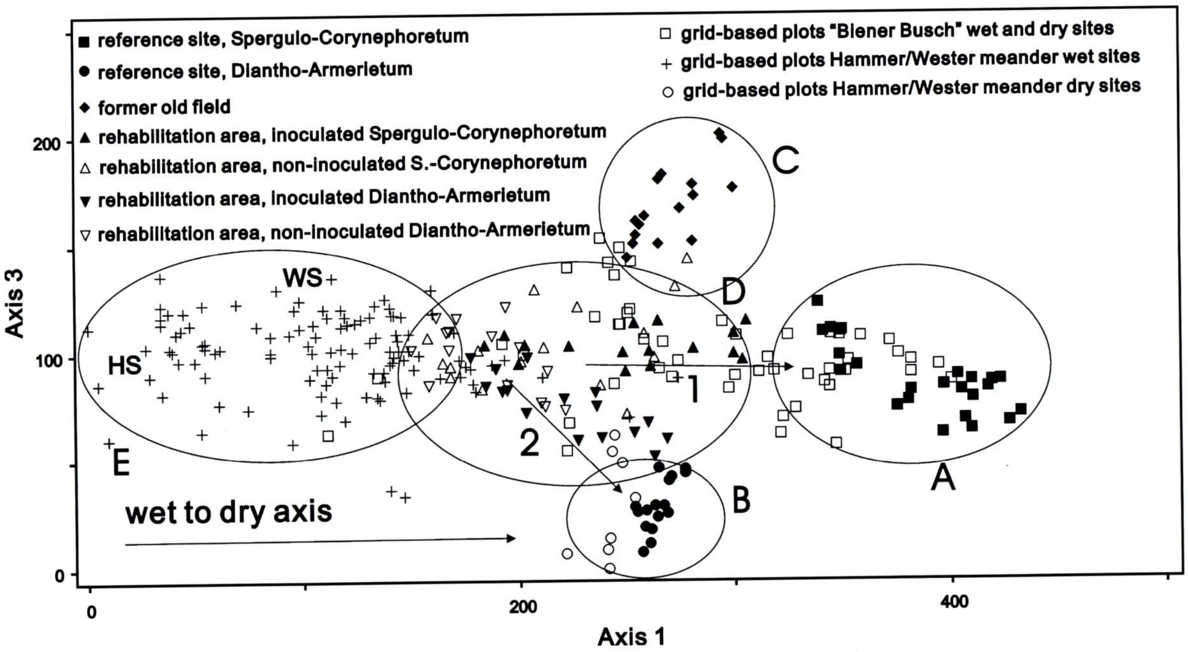

Fig. 5. Detrended Correspondence Analysis (DCA) of all vegetation plots (permanent plots with or without grazing and grid based permanent plots) in the reference and rehabilitation areas. A: reference site with Spergulo-Corynephoretum; B: reference site with Diantho-Armerietum; C: former maize and cereal field; D: inoculated and non-inoculated sites of rehabilitation area including some grid plots of the reference area "Sandtrockenrasen am Biener Busch" (wet and dry sites); E: wet sites of "Hammer meander" (HS) and "Wester meander" (WS). Eigenvalues: axis 1 = 0.50, axis 3 = 0.11 (axis 2 = 0.16). 1, 2 = inoculation axis with Spergulo-Corynephoretum (1), Diantho-Armerietum (2).

Table 4. Presence table of permanent plot vegetation (1, 2 … = occurrence in 1, 2, … permanent plots, abundance data are not published): Ct = Spergulo-Corynephoretum typicum; Cc = Spergulo-Corynephoretum cladonietosum; DA = Diantho-Armerietum; A = former maize and cereal field; CI = Spergulo-Corynephoretum inoculated; DI = Diantho-Armerietum inoculated; CN = Spergulo-Corynephoretum non-inoculated; DN = Diantho-Armerietum non-inoculated; B = nature reserve area "Sandtrockenrasen am Biener Busch"; H = "Hammer meander"; W = "Wester meander"; 0 = without grazing impact; g = grazed. * = only one plant individual. 36 species without indicator value are not printed.

vegetation type	Ct	Ct	Cc	Cc	DA	DA	A	A	CI	CI	DI	DI	CN	CN	DN	DN
site type	R	R	R	R	R	R	F	F	Rh	Rh	Rh	Rh	Rh	Rh	Rh	Rh
area	B	B	B	B	H	H	B	B	H,W	H,W	H,W	H,W	H,W	H,W	H,W	H,W
grazing	0	g	0	g	0	g	0	g	0	g	0	g	0	g	0	g
permanent plot	IV/V	IV/V	I	I	I/II	I/II	II/III	II/III	III-VI	III-VI	III-VI	III-VI	III-VI	III-VI	III-VI	III-VI
number of relevés	2	2	1	1	2	2	2	2	4	4	4	4	4	4	4	4
Spergulo-Corynephoretum																
Carex arenaria	2	2	1	1	1		1		3	1	1	1	2	3	2	
Corynephorus canescens	2	2	1	1					4	4	3	3	2	2	2	1
Festuca filiformis	2	1	1	1		1			4	4	1	2				
Aira praecox	2	2		1				1		2	1	3				
Teesdalia nudicaulis	2	2	1	1						2		2				1
Polytrichum juniperinum (B)		1		1			1	1	4	4	1					
Sedum acre	1	2							1	1	1		1			
Polytrichum piliferum (B)	2	2	1	1					2							
Campylopus introflexus (B)	2	1	1	1					1							
Cladonia furcata (L)	2	2	1	1					1							
Cladonia pyxidata agg. (L)	1	2	1	1												
Scleranthus annuus agg.		1									2	2				
Spergula morisonii		1		1												
Arenaria serpyllifolia	1	2														
Sperg.-Coryn. cladonietosum																
Cladonia uncialis (L)			1	1					2	1						
Cladonia arbuscula (L)			1	1					2	1						
Cladonia portentosa (L)			1	1					2	1						
Dicranum scoparium (B)	2		1	1												
Cetraria aculeata (L)	1		1	1												
Cladonia phyllophora (L)		1	1													
Calluna vulgaris			1	1												
Cladonia ciliata (L)			1	1												
Cladonia coccifera (L)			1	1												
Cladonia floerkeana (L)			1	1												
Cetraria islandica (L)			1													
Diantho-Armerietum																
Ranunculus bulbosus					2	2		1	2	3	1	2	1	2	2	2
Dianthus deltoides					2	2					4	4	1*		1*	
Anthoxanthum aristatum										1	2	2			2	2
Galium verum					2	2					1				1	
Sedum reflexum					1											
former old field																
Festuca brevipila							1	1								
Hieracium pilosella							1									
Verbascum nigrum							1									

former old field/rehabil. area																
Elymus repens	1	1					2	2	4	4	2	4	4	4	4	4
Holcus lanatus							1	2	3	4	3	3	2	2	4	3
Trifolium repens							1	2	2	3	3	2	3	2	3	3
Cirsium arvense							1		1	3	3	3	2	1	3	3
Lolium perenne								1		2	1	2	1	1		3
Dactylis glomerata							1	1			1	1			1	1
Vicia angustifolia							2	1			1				2	
rehabilitation area																
Tanacetum vulgare					1	1			2	2	2	3	2	2	4	3
Equisetum arvense									2	2	3	2	2	2	3	3
Juncus effusus									1	1	1	1	1	1	2	2
Vicia cracca									2	1	1	1	1	1	1	1
Pinus sylvestris juv.									3	2	3	2	2	2	4	2
Conyza canadensis									1	2	3	3	1	2	4	3
Tripleurospermum maritimum									1	1	1		2	1	1	3
Juncus bufonius									1	1		1	1	1	1	1
Artemisia vulgaris									1	2		1		2	2	1
Spergula arvensis										1		1		1	1	2
Apera spica-venti										1	2			2	2	2
Rumex crispus										1		1		1	2	1
Arrhenatherum elatius											1	1			1	1
Trifolium pratense											1	1			1	1
Rumex acetosa										1		1		1		2
Salix viminalis juv.										2				1	2	1
Salix caprea juv.										2				1	1	2
Carex muricata agg.											1		1		1	1
Ranunculus repens											1				1	1
Vulpia myuros											1	1				
Festuca pratensis														1		1
Poa trivialis											1		1			
Fallopia convolvulus																1
Alnus glutinosa juv.															1	
Cardamine hirsuta																1
Poa annua																2
Koelerio-Corynephoretea																
Rumex acetosella	2	2	1	1	2	2	2	2	4	4	4	4	4	4	4	4
Agrostis vinealis	2	2	1	1	2	2	1	1	3	4	4	4	1	1	1	
Ornithopus perpusillus								1	2	3	3	3	4	2	3	2
Herniaria glabra									2	1	1		2	1	2	1
Erophila verna	1	1			1					1					1	2
Vicia lathyroides							2	2	1	1					1	3
Cerastium semidecandrum	2	2						1		1						
Trifolium arvense		1					1	2	1							
Trifolium campestre							1	2								
Erodium cicutarium		1							1							
Filago minima									2	2						
Jasione montana									1							
Aira caryophyllea										1						

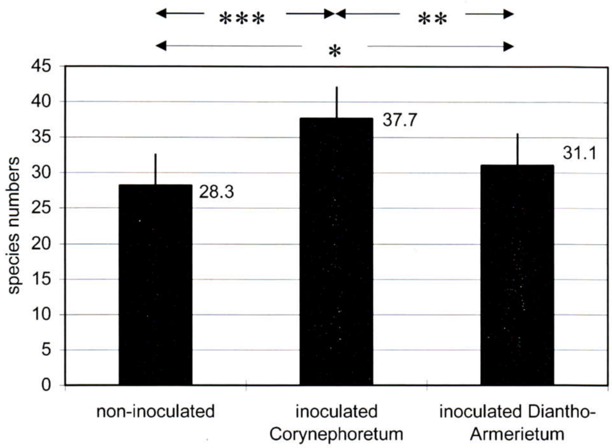

Fig. 6. Species numbers on non-inoculated plots and plots inoculated with Corynephoretum and Diantho-Armerietum plant material (Mixed linear model, SAS proc mixed, * p(F) < 0.05, ** p(F) < 0.01, *** p(F) < 0.001).

Corynephoretum reference sites (Spergulo-Corynephoretum typicum: 0.02–0.04 %; Remy & Menzel 2004) as well as those mentioned in the literature (0.013–0.078 %, Glemnitz et al. 1998; 0.09–0.2 %, Christiansen 2000). Concerning phosphorus, the levels in the new sand surface (15.4–23.7 mg P/kg) were higher than those of Corynephoretum reference sites (Spergulo-Corynephoretum typicum 5.3–11.2 mg P/kg; Remy & Menzel 2004) but lower than mentioned in the literature (28.7–30.7 mg P/kg, Glemnitz et al. 1998). The P-contents of fields were much higher (37.0–94.3 mg P/kg; Oehmichen 1983) than those of the rehabilitation sites.

In this region, the development of river dunes and moving sand formations goes back to early postglacial times and became most intense owing to human impact in the 19th Century due to woodland clearance and heath management including sod harvesting (Pyritz 1971). By shaping a true to nature relief, we created the suitable initial structures and conditions for the redevelopment of a diverse pasture landscape including potential stands of Spergulo-Corynephoretum and Diantho-Armerietum (Remy & Zimmermann 2004).

Due to the pioneer character of many alluvial plant communities, dynamic processes are indispensable for a successful rehabilitation of alluvial landscapes. Thus, an important factor initiating dynamic processes is the re-instatement of the flood regime. This is reflected by the large amount of sandy material deposited during one winter flood. These areas are probably the "nuclei" for the creation of new river dune systems. These inoculated "neo-dunes" will be a source for new colonization processes in the future.

One goal was to restore river dune vegetation according to the Flora-Fauna-Habitat directive (SSYMANK et al. 1998). Due to former anthropogenic changes of the landscape and intensification of agricultural management, autochthonous seed banks (VAN DER VALK & PEDERSON 1989; PUTWAIN & GILLHAM 1990; JENTSCH 2001) had totally disappeared in the rehabilitation areas. Moreover, most of the endangered plant species of sand dunes do not have any dispersal strategies covering long distances. Plant species of sand ecosystems mainly disperse by anemo- and zoochory. They are now only found in fragmented and small areas; in the case of Spergulo-Corynephoretum situated kilometres away (OSTENDORP 2001), in the case of Diantho-Armerietum in extremely small areas. Contrarily, hydrochoric plant species are expected to colonize the rehabilitated area by natural dispersal processes (BISCHOFF 2002; GROOTJANS et al. 2002). Therefore, inoculation by diaspore and plant material (including a diverse lichen flora) from mown and raked source areas turned out to be the only successful rehabilitation tool. In a pilot study carried out in the northern Upper Rhine area we examined the re-establishment of plant communities of sand ecosystems after inoculation with mown and raked material or sods under grazing impact (STROH et al. 2002). The combination of mown and raked plant material was assumed to be the most suitable method for the establishment of sand ecosystem plant communities (DONATH et al. 2003). Other methods (e. g. sod or soil transplantation; BROWN & BEDFORD 1997; BURKE 1997; BANK et al. 2002) were considered unsuitable or too expensive.

Comparing the species composition of reference sites in rehabilitation areas indicate that the inoculation concept has initiated a successful development to restore plant communities. The vegetation processes on non-inoculated sites exhibit high stochasticity without any clear direction of development.

According to TILMAN (1997) coexistence of many different species in grassland habitats might be possible, although species saturation can only be observed in very rare cases. Our hypothesis is that these high species numbers on inoculated plots only represent a transition stage, after which the species numbers will decline to a level similar to that observed in the reference plots. The transition stage is a blend of species characteristic for the stochastically first stage and by the inoculated target species.

A long-term approach should prevent vegetation succession and guarantee a dynamic system of pioneer communities by grazing impact (BAKKER et al. 1983; OLFF et al. 1999; SCHWABE et al. 2002; STROH & KRATOCHWIL 2004; STROH et al. 2004).

Both flood and grazing regimes, at different scale levels and with different disturbance forces, contribute to the development of a highly dynamic ecosystem. In contrast to the situation prior to rehabilitation now a high diversity of habitat types has been able to develop, similar to that in the reference area of the nature reserve "Sandtrockenrasen am Biener Busch".

Acknowledgements

The project was carried out in the framework of a "Testing and development project" funded by the German Federal Agency for Nature Conservation (BfN) and supported by the German Ministry of Research and Technology (BMBF); No. 01LN0003. The studies have been made possible by the cooperation with the "Landkreis Emsland" (Meppen) and the "Bezirksregierung Weser-Ems" (Oldenburg). We also thank the owners of the cattle for their cooperation; R. CEZANNE and M. EICHLER for field assistance; U. MENZEL, A. MÖHLMEYER and A. TSCHUSCHKE for technical support and C. STORM for statistical help. B. PAHLMANN (Osnabrück) and A. THORSON (Oxford) improved the English text; A. D. BUIJSE, H. COOPS and an anonymous referee gave valuable comments for improvement.

References

AERTS, R., HUISZOON, A., VAN OOSTRUM, J.H.A., VAN DE VIJVER, C.A.D.M. & WILLEMS, J.H. (1995): The potential for heathland restoration on formerly arable land at a site in Drenthe, the Netherlands. – J. Appl. Ecol. **32**: 827–835.

ASSMANN, T. & KRATOCHWIL, A. (1995): Biozönotische Untersuchungen in Hudelandschaften Nordwestdeutschlands – Grundlagen und erste Ergebnisse. – Osnabrücker Naturwiss. Mitt. **20/21**: 275–337.

BAKKER, J.P., DE LEEUW, J. & VAN WIEREN, S.E. (1983): Micro-patterns in grassland vegetation created and sustained by sheep-grazing. – Vegetatio **55**: 153–161.

BAKKER, J.P., GROOTJANS, A.P., HERMY, M. & POSCHLOD, P. (2000): How to define targets for ecological restoration. – Appl. Veg. Science **3**: 3–6.

BANK, P., BEMMERLEIN-LUX, F. & BÖHMER, H.J. (2002): Übertragung von Sandmagerrasen durch Soden, Diasporenbank oder Heuauftrag? – Naturschutz u. Landschaftsplanung **2–3**: 60–66.

BARKMAN, J.J., DOING, H. & SEGAL, S. (1964): Kritische Bemerkungen und Vorschläge zur quantitativen Vegetationsanalyse. – Acta bot. Neerlandica **13**: 394–419.

BISCHOFF, A. (2002): Dispersal and establishment of floodplain grassland species as limiting factors in restoration. – Biolog. Conserv. **104**: 25–33.

BROWN, S.C. & BEDFORD, B.L. (1997): Restoration of wetland vegetation with transplanted wetland soil: an experimental study. – Wetlands **17**: 424–437.

BURKE, D.J. (1997): Donor wetland soil promotes revegetation in wetland trials. – Restoration & Managem. Notes **15**: 168–172.

CHRISTIANSEN, U. (2000): Zur Bedeutung der Stickstoffversorgung für den Sukzessionsverlauf von sandig-trockenen Ackerbrachen zu Sandmagerrasen. – Diss. Bot. **329**: 1–143.

CSAPODY, V. (1968): Keimlingsbestimmungsbuch der Dicotyledonen. – Académia Kiadó, Budapest, 286 pp.

DE WAAL, L.C., LARGE, A.R.G. & WADE, P.M. (eds.) (1998): Rehabilitation of Rivers. Principles and Implementation. – Landscape Ecol. Series: 331 pp. John Wiley & Sons, Chichester.

DONATH, T.W., HÖLZEL, N. & OTTE, A. (2003): The impact of site conditions and seed dispersal on restoration success in alluvial meadows. – Appl. Veg. Science **6**: 13–22.

GLEMNITZ, M., WURBS, A. & DIECKMANN, M. (1998): Bedeutung von Bodenreaktion und Nährstoffgehalt für das Vorkommen von Arten der Sandtrockenrasen auf Brachflächen. – Verh. Ges. Ökol. **28**: 529–535.

GROOTJANS, A.P., BAKKER, J.P., JANSEN, A.J.M. & KEMMERS, R.H. (2002): Restoration of brook valley meadows in the Netherlands. – Hydrobiologia **478**: 149–170.

JENTSCH, A. (2001): The significance of disturbance for vegetation dynamics. A case study in dry acid grasslands. – Diss. Univ. Bielefeld, 199 pp.

KENT, M. & COOKER, P. (1992): Vegetation description and analysis. – CRC, Boca Raon, 363 pp.

KRATOCHWIL, A. & ASSMANN, T. (1996): Biozönotische Konnexe im Vegetationsmosaik nordwestdeutscher Hudelandschaften. – Ber. Reinh.-Tüxen-Ges. **8**: 237–282.

KRATOCHWIL, A., FOCK, S., REMY, D. & SCHWABE, A. (2002): Responses of flower phenology and seed production under cattle grazing impact in sandy grasslands. – Phytocoenologia **32**: 531–552.

KROLUPPER, N. & SCHWABE, A. (1998): Ökologische Untersuchungen im Darmstadt-Dieburger Sandgebiet (Südhessen): Allgemeines und Ergebnisse zum Diasporen-Reservoir und -Niederschlag. – Bot. Natursch. Hessen **10**: 9–39.

LITTELL, R.C., MILLIKEN, G.A., STROUP, W.W. & WOLFINGER, R.D. (2000): SAS System for Mixed Models. – Cary NJ (SAS Institute), 633 pp.

MULLER, F.M. (1978): Seedlings of the North-Western European Lowland. – Dr. W. Junk, The Hague & Boston, 664 pp.

OEHMICHEN, J. (1983): Pflanzenproduktion. Bd. **1**: Grundlagen. – Parey, Berlin, 532 pp.

OLFF, H., HUISMAN, J. & VAN TOOREN, B.F. (1993): Species dynamics and nutrient accumulation during early primary succession in coastal sand dunes. – J. Ecol. **81**: 693–706.

OSTENDORP, J. (2001): Pflanzensoziologische Analyse der Sandtrockenrasen im Emsland. – Diplomarb. Univ. Osnabrück, 107 pp.

PALMER, M.A., AMBROSE, R.F. & POFF, N.L. (1997): Ecological theory and community restoration ecology. – Restoration Ecol. **5**: 291–300.

POTT, R. & HÜPPE, J. (1991): Die Hudelandschaften Nordwestdeutschlands. – Abh. Westf. Mus. Naturkunde **53**: 1–313.

PUTWAIN, P.D. & GILLHAM, D.A. (1990): The significance of the dormant viable seed bank in the restoration of heathlands. – Biol. Conserv. **27**: 1–16.

PYRITZ, E. (1971): Binnendünen und Flugsandebenen im Niedersächsischen Tiefland. – Göttinger Geograph. Abh. **61**: 1–153.

REMY, D. & MENZEL, U. (2004): Nährstoffstatus und Phytomasse beweideter und unbeweideter Sandrasen in den Flussauen von Ems und Hase (Emsland, Niedersachsen). – In: SCHWABE, A. & KRATOCHWIL, A. (eds.): Beweidung und Restitution als Chancen für den Naturschutz? NNA-Berichte **17**: 91–109.

RIECKEN, U., FINCK, P. & SCHRÖDER, E. (2001): Tagungsbericht zum Workshop „Großflächige halboffene Weidesysteme als Alternative zu traditionellen Formen der Landschaftspflege". – Natur u. Landschaft **76**: 125–130.

SCHWABE, A., REMY, D., ASSMANN, T., KRATOCHWIL, A., MÄHRLEIN, A., NOBIS, M., STORM, C., ZEHM, A., SCHLEMMER, H., SEUSS, R., BERGMANN, S., EICHBERG, C., MENZEL, U., PERSIGEHL, M., ZIMMERMANN, K. & WEINERT, M. (2002): Inland Sand Ecosystems: dynamics and restitution as a consequence of the use of different grazing systems. – In: REDECKER, B., FINCK, P., HÄRDTLE, W., RIEKEN, U. & SCHRÖDER, E. (eds.): Pasture Landscapes and Nature Conservation: 239–252. Springer, Berlin, Heidelberg.

SSYMANK, A., HANDKE, U., RÜCKRIEM, C. & SCHRÖDER, E. (1998): Das europäische Schutzgebietsystem Natura 2000. – Schr.-R. f. Landschaftspfl. u. Natursch. **53**: 1–560.

STORM, C. & BERGMANN, S. (2004): Auswirkungen von Schaf-Beweidung auf die Nährstoffdynamik von Offenland-Sand-Ökosystemen in der nördlichen Oberrheinebene. – In: SCHWABE, A. & KRATOCHWIL, A. (eds.): Beweidung und Restitution als Chancen für den Naturschutz? NNA-Berichte **17**: 79–90.

STROH, M. & KRATOCHWIL, A. (2004): Vegetationsentwicklung von restituierten flussnahen Sand-Ökosystemen und Feuchtgrünland im Vergleich zu Leitbildflächen (Emsland, Niedersachsen). – In: SCHWABE, A. & KRATOCHWIL, A. (eds.): Beweidung und Restitution als Chancen für den Naturschutz? NNA-Berichte **17**: 55–68.

STROH, M., KRATOCHWIL, A. & SCHWABE, A. (2004): Fraß- und Raumnutzungseffekte bei Rinderbeweidung in halboffenen Weidelandschaften: Leitbildflächen und Restitutionsgebiete im Emsland (Niedersachsen). – In: SCHWABE, A. & KRATOCHWIL, A. (eds.): Beweidung und Restitution als Chancen für den Naturschutz? NNA-Berichte **17**: 133–146.

STROH, M., STORM, C., ZEHM, A. & SCHWABE, A. (2002): Restorative grazing as a tool for directed succession with diaspore inoculation: the model of sand ecosystems. – Phytocoenologia **32**: 595–625.

THOMPSON, K., BAKKER, J. & BEKKER, R. (1997): The soil seed banks of North West Europe: methodology, density and longevity. – Cambridge Univ. Press, Cambridge, 276 pp. and disc.

TILMAN, D. (1997): Community invisibility, recruitment limitation, and grassland biodiversity. – Ecology **78**: 81–92.

VAN DER VALK, A. & PEDERSON, R.L. (1989): Seed banks and the management and restoration of natural vegetation. – In: LECK, M.A., PARKER, V.T. & SIMPSON, R.L. (eds.): Ecology of Soil Seed Banks: 329–346.

VAN DIGGELEN, R., GROOTJANS, A.P. & HARRIS, J.A. (2001): Ecological restoration: state of the art or state of the science? – Restoration Ecol. **9**: 115–118.

WHITE, P.S. & WALKER, J.L. (1997): Approximating natures variation: selecting and using reference information in restoration ecology. – Restoration Ecol. **5**: 338–349.

Received: 29 September 2003; revised: 8 June 2004; accepted: 13 July 2004.