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Changes in Physical and Chemical Properties of Fen Soils Induced by Long-term Drainage, Followed by Recent Rewetting

Jutta Zeitz and Andreas Gensior*

ABSTRACT

Intensive agricultural use of fen soils in eastern Germany elicits soil formation processes that may lead to soil degradation. The soil properties of fen soils are described according to substratum-horizon groups. The ecological effects and proposals of an alternative fen use are discussed. Since 1997, a highly degraded fen area (10 ha) has been rewetted by damming up drainage canals and surface irrigation for restoration and cultivation of reed as an industrial raw material. Beneath ecological and economical investigations, the project is joined by hydrological and soil scientific research. With the rewetting of the area, there have been remarkable changes in redox potential joined by a decrease of dissolved elements in soil solution.

INTRODUCTION

Fen soils have been used intensively for agriculture during the past 30 years in eastern Germany. The management of fen soils, following the former German Democratic Republic's objectives of economic independence and high productivity, led to a drastic decrease in soil fertility. The main cause was the lowering of the groundwater level to permit intensive utilization. This drainage made the sites accessible at all times even for heavy machines with a high-pressure index. Degradation and drying out of the fens were increased by intensive grass cultivation with regular cuttings three to four times a year. Soil degradation was increased by the high calcium carbonate content of the glacial till around the fenland and by the relatively dry climate in eastern Germany. This intensive agricultural use modified the soil parameters to such an extent that the peat underwent soil formation with the development of several diagnostic soil horizons. If intensive agriculture reduces the fertility of fen soil below a certain value, it is said to be degraded. In fen soils, degradation means development of an earthy structure in the topsoil and of a highly segregated structure in the subsoil. More than 40% of fen soils in eastern Germany are degraded. The original functions of fens in the landscape have been largely lost, particularly with regard to the water regime and nutrient cycle.

Eventually, agriculture became unprofitable due to soil degradation and the damage to the environment was not any longer acceptable. New ways of utilizing fen soils had to be found which were not only economically and socially acceptable, but also ecologically compatible in the sense of sustainable development. Less intensive cultivation alone cannot stop the degradation. Restoration of a fenland is only possible by rewetting. An interdisciplinary research project entitled "Restoration of a degraded fen by cultivation of reed as industrial plant using purified waste water" was therefore promoted by the Federal German Foundation for the Environment (DBU). In this project, a 10 ha area of degraded fen soil in the Randow-Welse landscape (100 km NNE of Berlin) was selected as a trial restoration site. After planting typical fen vegetation (e.g. reeds and sedge), the degraded fen flooded again using water from a ditch nearby. From the viewpoint of soil conservation, one of the most important aims of the project is to reactivate the natural functions of a fen such as being an element sink and water reservoir in the landscape. A special experimental area (6250 m^2) at the trial site was set up to investigate element fluxes and to make out a balance sheet for carbon. This paper describes the changes that have taken place in soil properties in fens in the eastern part of Germany within the last 30 years: firstly, due to soil degradation because of drainage and intensive agricultural use, and secondly, due incipient recovery because of rewetting.

METHODS

Changes in selected parameters of fen soils were investigated by analysing water-retention curves and measuring the hydraulic conductivity of unsaturated soil (Vetterlein, 1968). Samples of topsoil were taken from the paludification mire "Upper Rhinluch" (fen landscape 70 km north-west of Berlin; about 8000 ha) and typical soil parameters measured. The unit water content as a special parameter (UWC, no dimensions; German Democratic Republic standard TGL 24300/04), which is the water content of a peat sample after consolidation at a pressure of 100 kPa, was also determined. On the trail restoration site at four different depths, the composition of soil solution (monthly 24 parameters) and the redox potential were measured. In addition, the element deposition and the fluxes in the catchment were measured (Gensior et al., 1998, Gensior et al., 1999).

RESULTS

Universal pedogenic processes

The pedogenic processes result in the formation of typical organic soil horizons with distinctive soil properties.

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Table 1: Definitions and symbols of organic soil horizons (Bodenkundliche Kartieranleitung, 1994).

Horizon	Description
H	Horizon with more than 30 %wt. organic matter (peat), originating from the residues of peat-forming plants at the soil surface (peat) (universal description of all peat horizons)
Hm	H-horizon on the soil surface of intensive drained and tilled peatland, strongly humified (“earthified”), highly decomposed; dusty structure and highly water repellent when dry
Hv	H-horizon on the soil surface of drained peatland, poorly to moderately humified (“earthified”) by aerobic mineralization and humification, crumb or fine sub angular structure
Ha	Subsoil horizon of thoroughly drained peat land, “aggregate horizon”; coarse to fine, angular, blocky structure caused by shrinking and swelling and the formation of vertical and horizontal shrinkage cracks
Ht	Subsoil horizon, “shrinkage horizon”, vertical cracks and coarse prismatic structure caused chiefly by shrinkage
Hw	H-horizon, affected by a fluctuating groundwater table or perched groundwater table, partially oxidized
Hr	H-horizon, permanently below the groundwater table and preserved in a reduced state

Table 2: Soil parameters for substratum-horizon groups comprised of mixed sedge-and-reed peat.

Horizon	Substratum-horizon group Substratum; classification parameter		PV	CPI	UFC	MPI	CPII
nHv	x<30; share of dry mass: 13...23 vol.%	X	81.6	14.4	37.6	30.5	7.1
	n:79	s	4.8	5.5	12.9	11.8	6.3
nHm	x<30; share of dry mass: 18...25 vol.%	X	79.1	24.4	27.3	21.0	6.3
	n:27	s	2.8	7.6	5.9	6.9	8.5
nHa to 40 cm b.s	Hnp; Hnr/Hnp; share of dry mass:8...16 vol.%	X	87.8	16.4	41.6	34.9	6.7
	n:49	s	3.2	7.1	11.4	9.0	6.3
nHt >40 cm b.s.	Hnr/Hnp; share of dry mass: 9...16 vol.%	X	88.3	14.7	44.2	34.9	9.3
	n:30	s	2.6	7.1	10.8	10.9	7.2
nHr	Hnr/Hnp with x<20; share of dry mass: 7...13 vol.%; n:129	X	91.1	14.2	58.3	41.6	17.4
		s	1.9	6.5	4.2	6.7	10.5

nHv, nHm, nHa, nHt and nHr see table 1; nH = fen (in German "Niedermoor") horizon; Hnp = reed peat; Hnr = sedge peat; CPI = coarse pores >50 µm (vol.%); Hnr/Hnp = mixed sedge-and-reed peat; PV = pore volume (vol.%); CPII = coarse pores 10–50 µm (vol.%); x = ash (w/w); MPI = medium pores 3–10 µm (vol.%); UFC = useful field capacity (vol.%); b.s. below surface; n = number of samples; s = standard deviation; X = mean.

Table 3: Selected ecological parameters of topsoils (0–30 cm) in fen soils of the Upper Rhinluch (Brandenburg).

Parameter	nHv			nHm		
	n	mean	standard deviation	n	mean	standard deviation
Share of dry mass (vol.%)	89	18.91*	2.37	100	21.28*	2.01
Ash (w/w)	89	19.68*	4.16	100	22.69*	4.84
Bulk density (g/cm^3)	89	30.48*	4.07	100	34.76*	3.64
Unit water content (without dimension)	66	2.02*	0.27	83	1.61*	0.19

* level of significance α=0.05, n = number of samples

For the first time in Germany, the 4th edition of “Bodenkundliche Kartieranleitung” (1994), the official German guidelines for soil mapping, shows several horizons derived from an organic substratum in a classification that diverges from the FAO-classification. This new classification of organic soils replaces the much simpler one in previous editions of the guidelines, which classified peat soils mainly on the basis of geogenic and anthropogenic parameters. There were two main reasons for a more detailed classification of peat soils:

1) The pedogenic processes initiated by drainage and agriculture are given more consideration, and
2) Unambiguous symbols must be assigned to the various horizons as a prerequisite for more efficient computer use (Benne et al., 1992).

Consequently, seven horizons with different pedogenic parameters can be described right in the field (Table 1).

From the viewpoint of soil conservation, the Hm- and Ha-horizons are considered to be degraded. The changes that have occurred in the properties of the peat due to pedogenic processes are highly significant when future peat land utilization, conservation, and regeneration are being planned.

Changes in soil parameters due to soil degradation

Analysis of water retention curves from fen soils has shown that, owing to drainage and aeration, the soil properties differ mainly between the various horizons; however, within some horizons they can be shown to differ as a function of the kind of peat. In fen soils strongly anthropogenic influence, the pedogenic differences mask the botanical differences. Altogether 14 substratum-horizon groups were identified from the data under review (Zeitz, 1992). The mixed sedge-and-reed peat, which is quite common in fenlands, is used as an example to illustrate that the proportions of the various pore classes change in the course of soil development and horizon formation (Table 2).

Assuming that all substratum-horizon groups (Table 2) have an identical initial substratum, these groups could be considered to exhibit, from bottom to top, stages of increasing soil development and, hence, of increasing amounts of swelling and shrinkage. The pore volume decreased slightly, from 91.1 % in the nHr-horizon to 87.8 % in the nHa-horizon, while the proportion of coarse pores and, consequently, the air capacity increased from 14.2 to 16.4 %. The change in soil properties permitted increased aeration. Shrinkage went hand in hand with a decrease in the volume of coarse and medium pores, which drain slowly. Compared with the initial substrate, the nHr-horizon, which was permanently below the groundwater table, the CP-II and MP-II (< 0.2 – 3 μm) fractions in the strongly segregated nHa horizon decreased by 62 % and 46 %, respectively. This had a direct impact on the hydraulic conductivity and on capillary rise from the groundwater. The more the peat was decomposed, the lower the hydraulic conductivity became. Calculation of the capillary rise of given quantities of water (e.g., flux 0.3 cm d^{-1}) using van Genuchten's (1980) method and a one-layer model gave water transport values of less than 10 cm in the highly segregated horizons nHv and nHm (Zeitz, 1992).

From the soil protection and agronomic points of view, it is very important to assess the soil properties in the top 30–40 cm of fen soils, as this is the main rhizosphere of most grassland plants. During development of soil from the nHv-horizon to the nHm-horizon, the useful field capacity – as one of the major ecological soil parameters – decreased from about 38 to as little as 27 % volume. Assuming topsoil with an average rooting depth of 30 cm, only about 80 mm of soil water was still available to the plants. Under the climatic conditions in Brandenburg, this increased the danger of soil desiccation and wind erosion.

Determination of the unit water content showed that soil degradation lead to a considerable decrease in water-retention capacity. Investigations of the Upper Rhinluch paludification mire, which has been under intensive agricultural use for more than 200 years, revealed obvious symptoms of degradation (Table 3).

The unit water content (UWC) is a rough measure of how much the structure of the original peat has been retained. The lower the UWC, the lower the water-retention capacity and the more advanced the soil development. In peat soils that had reached an advanced stage of soil development, the structure was similar to the single-grain structure of mineral soils. The UWC allowed four degrees of peat decomposition (from slightly earthy peat with UWC > 2.2 to strongly decomposed peat with UWC < 1.5) to be distinguished. Due to soil degradation, the unit water contents of the nHm-horizon were 20 % lower than those of the nHv-horizon (Table 3). The topsoil was densely packed and the physical parameter values of the strongly decomposed nHm-horizon differed significantly from those of slightly earthy peat.

All results showed that drainage and agricultural use of organic soils gave rise to pedogenic processes, which lead to the development of distinct soil horizons. These horizons showed a high degree of soil degradation. Such fen soils did not fulfil their original functions in the landscape. Since decreasing the intensity of land use did not arrest soil degradation sufficiently, it was necessary to establish alternative types of land use for fen soils.

Changes in soil properties because of rewetting

CO_2-C - efflux

Due to the rewetting, measured the CO_2- efflux from the fen soil decreased considerably (Fig. 1). The methods of rewetting the fen influenced the CO_2- efflux too. The efflux from excess flooded parts of the investigation site has been smaller than from irrigated.

The calculation of yearly CO_2-C losses based on these results were investigated by the method of Lundegardh (1927), which when neglecting factors could influence the CO_2 dynamic considerably. The CO_2-C efflux from a drained and rewetted fen soil (rewetted by damming up (flooded) and irrigation) (mean and [range] in CO_2-C g $(m^2*a)^{-1}$, estimated by release instalments) was the following: drained = 560 [344]; rewetted = 205 [124]; flooded = 143 [50] and irrigated = 267 [199]. Nevertheless, the values showed the same order for the drained variant, which were similar to those reported by other authors for similar locations (Mundel, 1976). Values for a completely rewetted fen are not known. Although the quantitative evaluation of these results required a careful interpretation, the results pointed out that organic substances were less decomposed and the gaseous CO_2-C effluxes from the fen soil decreased because of the rewetting.

The development of the E_h - values were elucidated at the beginning of flooding between February and March 1997 by significant peaks at all depths. These peaks mainly were due to the supply of fresh water, which was still rich on oxygen. The oxygen would be used up within a few hours. While the rewetting caused dramatic changes in the redox potential in the upper horizons after a short time, the E_h - values for the deeper horizons were only changed slightly, because they were influenced by groundwater before flooding (Fig. 2).

On average, the restoration measures have led to continuously anaerobic, strongly reductive conditions in the whole fen soil. The significant short time peaks in all horizons showed that partially oxidative conditions could occur at any time and anywhere in the soil after rewetting the fen soil completely. Reasons for these abrupt changes in redox potential were slight variations of water level, in the case of irrigation oxygen rich fresh a water supply, oxygen transferred by the reed rhizomes into the soil, air added to water and differing hydraulic conductivities due to preferential flow. A working drainage system influenced the redox conditions in the fen soil, considerably. Additional investigations, which were carried out at the 45 and 75 cm depth in the acidic parts of the site resulted in positive redox potentials (E_h = 245-459 mV). In the area around the drainage tubes, saturated water conductivity increased, with more water passing through soil in time. Therefore, oxygen rich water was supplied and drawn off permanently, and

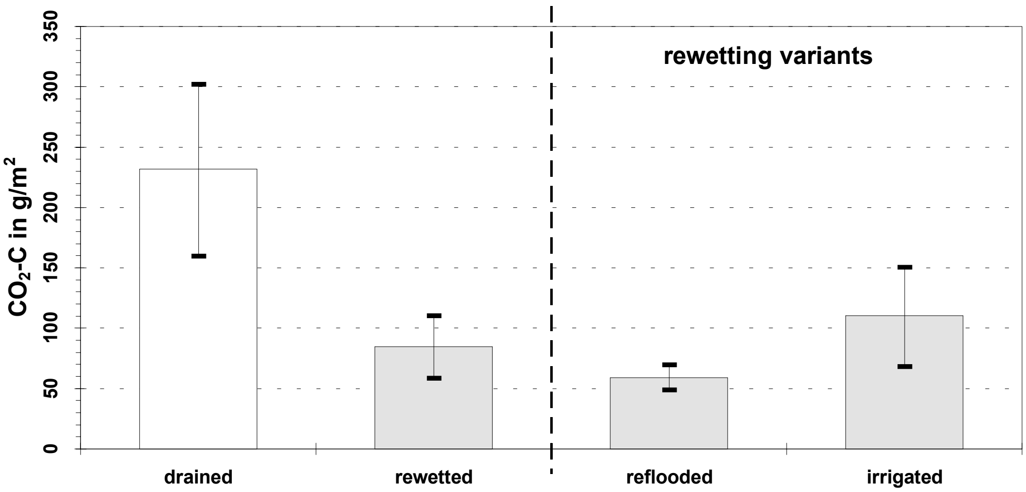

Figure 1: Sum of gaseous CO_2-C-losses (mean, minimum and maximum in g m^{-2}) during 151 days from a drained and rewetted fen soil.

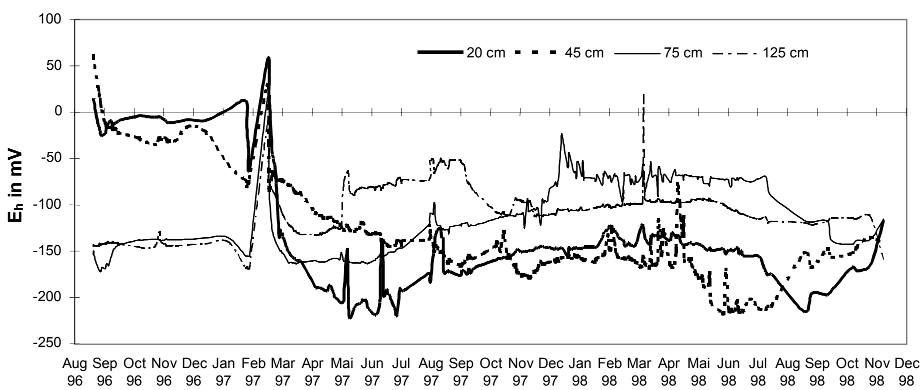

Figure 2: Mean E_h-values (mV) in four depths of degraded fen.

causing a partial to fully oxidative condition.

The pH values of the soil solution changed slightly due to flooding. While in the 45 cm and 75 cm depths there were no changes in the pH, the pH decreased slightly at the 20 and 125 cm depths. While the temporary variability was very small in all horizons, the spatial heterogeneity at the 45 and 75 cm depths was prominent. The low pH values at 45 and 75 cm was caused by the formation of sulfuric acid from the oxidation of sulfides. The reason for these processes occurred was caused by the changes in the soil aeration due to the drainage system. Because of the drainage system, the production of acid was very high in the fen soil after rewetting. Subsequently the transfer within the fen is dominant and lead to irreversible acidification (the decreasing pH in 125 cm resulted from these processes). The element concentrations in the soil solution were very high in all horizons before flooding (Fig. 3A). The composition of the soil solution was dominated by calcium (61-79%) and sulfate (62-82%) in all horizons.

Concerning the anions, chloride (8-11%) and bicarbonate (7-27%) showed appreciable concentrations. Due to the pH, the bicarbonate concentrations in the partially acid horizons (45 cm, 75 cm) were much lower than in the depth of 20 cm and 125 cm. In all horizons, organic anions (< 0.5%) and nitrate appeared only in trace amounts. Phosphate was not detectable in soil solution. Of the cations, Mg^{2+} (9-12%) and Na^{+} (12-15%) showed appreciable concentrations, whereas K^{+} (< 0.3%) was found only in trace amounts. $NH^{+}4$-, H^{+}-, Al^{3+}- and the heavy metals, especially Fe^{2+} (13% in the depth of 75 cm), were detected in significant amounts only in the acid horizons (Fig. 3A). Fourteen month after flooding, the element concentrations at the 20 and 45 cm depths decreased significantly (Fig. 3B). The concentrations at 125 cm increased, whereas at 75 cm no changes were found. At 125 cm depth the concentrations of most elements measured increased due to rewetting, the changes in the upper horizons were more significant. Beside the dramatically decreased concentrations of Ca^{2+} and SO_4^{2-}

(also Mg^{2+}, Na^{+}, Cl^{-}, Al^{3+} concentrations decreased), the concentrations of some elements like K^{+}, P, and heavy metals (especially Fe and Mn) increased, particularly in the top horizon, with time after rewetting.

The absence of nitrate concentrations after flooding indicates denitrification occurred. Besides displacement, the increase of some element concentrations was mainly caused by the solution of iron oxides and hydroxides. Due to the decreased redox potential in the upper horizons, this process started three month after rewetting measure and led to a distinct increase of Fe in soil solution, particularly in the top horizons. In addition, elements, which were associated with the iron oxides, like P, Mn, and as were released and gradually increased concentrations could be detected. This fact is alarming because the content of iron is very high in the fen soil (about 100 g kg^{-1}) and 80-90 % of this iron exists in form of amorphous, crystalline oxides or hydroxides (Gensior et al., 1999). Additionally the As contents are extremely high (≤ 200 mg kg^{-1}).

The results of the element fluxes in the fen soil system and a balance sheet for the first year after rewetting showed three groups of elements in the fen soil system, namely elements with a:

- Positive balance - sheet:
  dissolved organic C, K^{+}, NH_4^{+}, NO_3^{-} and H^{+}
- Consistent balance - sheet:
  Si^{4+}, Al^{3+} and HCO_3^{-}
- Negative balance - sheet:
  Ca^{2+}, Mg^{2+}, Na^{+}, Fe, Mn, Cl^{-} and SO_4^{2-}

The results showed that the fen soil has primarily functioned as an element source due to the rewetting (Table 4).

While the output of Ca and sulfate has been extremely large, even elements like Fe and Mn increased due to the rewetting and reached alarming concentrations for trace metals. Generally, the output by leaching has been very large. The element fluxes were large in the parts of the experiment site, which were influenced by the drainage system. For example, the system output of SO_4^{2-}-S (125 cm) 6.3 t ha^{-1} in the rewetted areas in contrast with 4.2 t ha^{-1} in the untreated areas. In addition, the differences in sulfur fluxes between 75 cm and 125 cm depth elucidate the influence of the drainage system. While in the acidic areas of the site the difference in SO_4^{2-} -S fluxes between the two

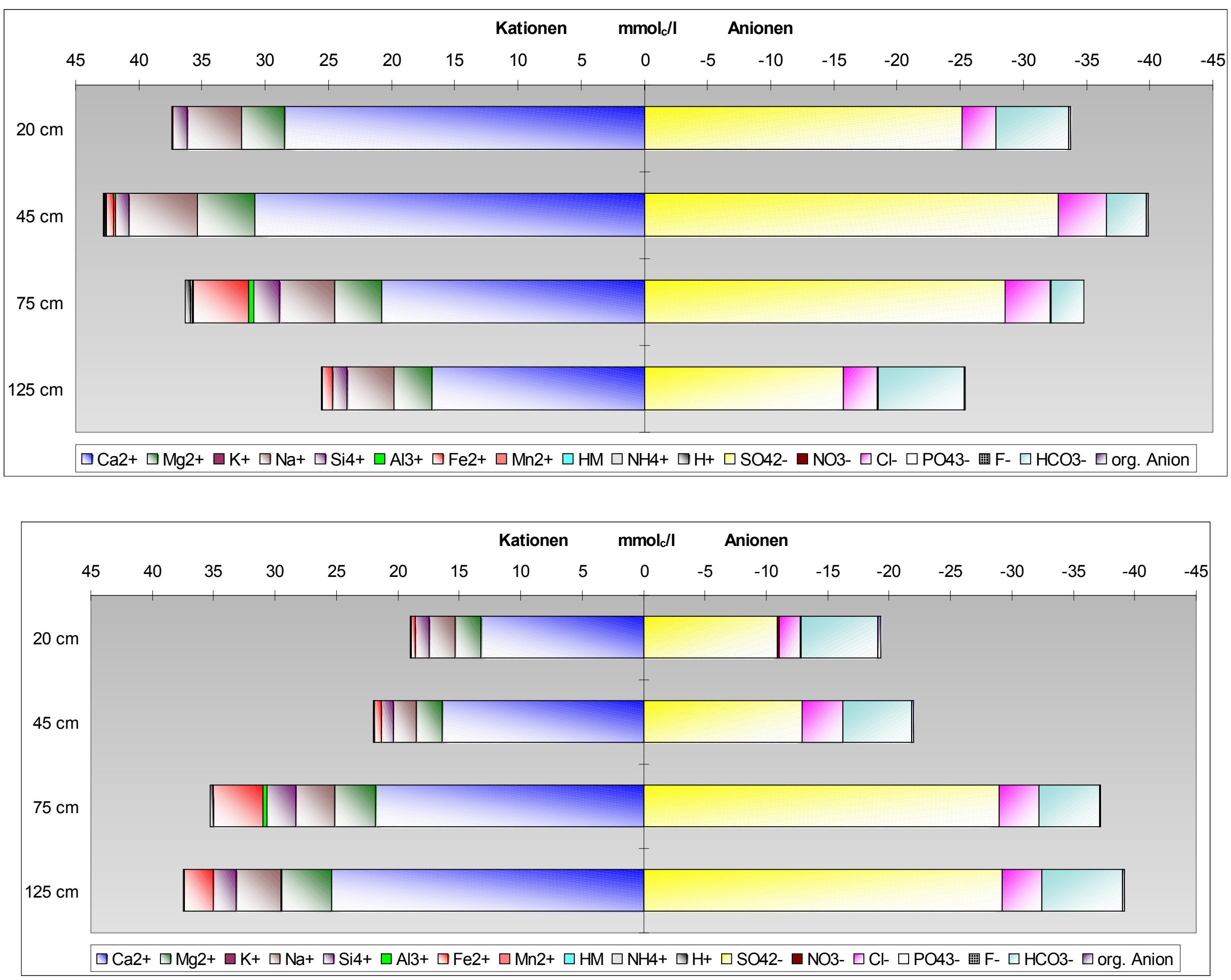

Figure 3: Mean composition of soil solution in 20 cm, 45 cm, 75 cm and 125 cm depth of the degraded fen soil at the beginning (A: before reflooding) and the end (B: after reflooding) of the investigations ($mmol_c$ l^{-1}; HM=Zn^{2+}+As^{3+}+Pb^{2+}+Cu^{2+}+Cd^{2+}+Hg^{2+})

Table 4: Annual element fluxes in the fen soil of the investigation site (sum of monthly means from April 97 to March 98 (Balance = precipitation + irrigation – 125 cm).

	kg ha^{-1}														g ha^{-1}
	DOC	Ca	Mg	K	Na	Si	Al	Fe	Mn	NH_4^+	NO_3^-	Cl^-	SO_4^{2-}	HCO_3^-	H
Precipitation	56	14	3	19	12	2	0.1	0.2	0.1	30	18	33	48	31	3.6
Irrigation	101	1188	163	54	413	117	0.8	10	2	2	33	781	1344	4113	0.2
20 cm	212	3740	303	20	750	108	0.5	73	27	6	25	782	6589	5295	0.4
45 cm	206	4815	384	15	972	101	3.2	99	12	13	15	1184	10918	3409	1813
75 cm	185	6124	537	27	1280	168	26	1134	27	62	4	1218	18666	3012	5182
125 cm	129	5854	504	38	1151	121	0.5	443	31	6	15	1203	14341	4154	2.7
Balance	28	-4652	-338	35	-726	-2	0.4	-433	-29	26	36	-389	-12949	-10	1.1

horizons amounts to 2.8 t ha^{-1} (flux in 75 cm = 9 t ha^{-1}), there was almost no difference in the flux in the undrained areas.

The considerable differences between the element fluxes in 75 and 125 cm depths were caused by leaching processes due to the drainage system (the dominant process), and the elements were removed from the soil solution by chemical processes like adsorption (due to the rewetting the content of organic C increased between 85 and 100 cm, subsequently increasing the caution exchange capacity) and precipitation (sulfides). The decreased flux of protons caused buffering (carbonate buffering, exchange buffering) and reduction.

SUMMARY AND PROSPECTS

The hitherto existing investigations have shown that the rewetting measure has led to a strong decrease in E_h in the top soil, consequently leading to permanent anaerobic and strongly reductive conditions in the whole fen soil. Therefore, the decomposition and humification of organic substances decreased and the CO_2 efflux was reduced. Whether or not the changes in CO_2 efflux are relevant with regard to climate depends mainly on the crosscheck with the increased CH_4 efflux. Because of these changes and the positive C and N balance of the fen ecosystem (gaseous CO_2 losses were compensated by the reed biomass), by the restoration action providing conditions for renewed peat growth were managed and therefore the requirements for the reactivation of the natural functions of the fen in the landscape ecology. The high water level in the experimental plots (compared with the surrounding area) and the effective drainage system elevated the potential gradient and lead to a large water consumption, and to partially oxidative and oxidative conditions, respectively in the fen soil. These conditions were the reason for the formation of acid, the subsequent acidification of the fen soil, and the mobilization, translocation, and leaching of nutrients and pollutants. These were leached very fast in appreciable amounts into the groundwater via the main ditch under these conditions. In addition, processes, which could lead to storage of mobilized nutrients and pollutants (e.g. the formation of sulfides) or to an elevation of pH, were reduced or totally prevented.

Due to of the totally changed conditions in the fen soil, the system was destabilized by rewetting. To stabilize the system, processes began that decrease of the element concentrations in the soil solution due to the formation of sulfides, adsorption, processes of translocation and leaching, increased solubilization of iron oxides and hydroxides, the release of associated elements, and increased leaching of nutrients and pollutants (distinctly influenced by the working drainage system). Due to rewetting, the fen has been in a transitional since at the end of the investigation period. How long the listed processes will be active, to what extent they will increase, decrease, or be replaced by others and if and when they will lead to the stabilization of the system can only be hypothesized. Results of this investigation make it possible to draw conclusions for the management of similar projects:

- Processes of rewetting should be carried out on larger areas in future times because the effects in the border areas of the experiment would be marginal. The consequence would be decreased amounts of water needed for rewetting. The latter is important with regard to the irrigation of wastewater.
- Any effective working drainage system must be closed. The consequence would be a distinctly decrease in redox potential and subsequent immobilization of nutrients and pollutants by reduction processes and by increasing pH. Furthermore, the amount of leached elements would be reduced, as would the consumption of water.
- The rewetting should not be undone. The consequence would be a distinct increase of redox potential and subsequent mobilization of stored nutrients and pollutants (especially heavy metals and acid).

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