First publ. in: Wetlands Ecology and Management 3 (1995), 4, pp. 233-248

Impact of winter reed harvesting and burning on the nutrient economy of reed beds

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Keywords: wetland management, *Phragmites* reeds, Lake Constance, littoral sediments

Abstract

The fringing reeds (*Phragmites australis* (Cav.) Trin. ex Steud., Poaceae) at Lake Constance-Untersee were mown or burnt in winter thereby drastically reducing the addition of decomposable organic matter to the sediment. The purpose of this study was to test whether or not this management significantly decreased the contents of organic matter and nutrients in the surface sediment layer and if the oxygen conditions in the within-reed water body improved. Hypotheses were tested by monitoring 6 treated reed beds and 3 reference fields over a period of up to 4 years. The sediment/water system of reed beds was found to be well buffered against the removal of the current year's crop of dead *Phragmites* straw, because only slight, and mostly insignificant, differences between treated and untreated reeds were detected. Hence, the benefit of winter reed harvesting to reduce nutrient overloading of the reed-belts and the 'die-back' of reeds remains dubious.

Introduction

The nutrient economy of the pelagic zone in shallow lakes is influenced by littoral vegetation and littoral sediments, because the littoral zone takes a great part of the total water volume, and a great portion of the total bottom area. The littoral vegetation functions as a filter for nutrients and particulate matter coming into the lake *via* surface runoff, diffuse sewage disposal, and nutrient rich ground water (Howard-Williams 1985, Hillbricht-Ilkowska and Pieczynska 1993). This is especially the case for fringing reed beds that accumulate allogenic inorganic matter, autogenic organic matter and nutrients. Thick peat layers can accumulate over centuries, due to the high annual biomass production, and the stability of reed communities.

Lake rehabilitation measures intending to protect a shallow water body from excessive nutrient input should take into account, therefore, the nutrient budget of fringing reed beds. In this context it seemed reasonable to enhance the nutrient export from the lake by harvesting the aboveground helophytic biomass (*e.g.*, Sieghardt and Maier 1985). It has been hypothesized that repeated treatment would cause the reed vegetation to become nutrient limited, and that the external nutrient inputs would be exploited to a higher degree than before. Furthermore, Schröder (1987) argued that winter reed harvesting and burning would be beneficial for the reeds themselves, thereby preventing the accumulation of nutrients and degradable organic matter that was thought to induce complete oxygen depletion in the within-reed water body and the development of reduced substances harmful to the *Phragmites* roots.

Full scale reed harvesting experiments at Lake Constance-Untersee have been conducted with the explicit objective of reducing organic matter and nutrient content of the top layers of the sediment. A second objective was subsequently introduced: reeds were mown to weaken the vitality of the common reed (*Phragmites australis* (Cav.) Trin. ex Steud., Poaceae) and give endangered wetland plant species the chance to grow and reproduce.

The influence of winter harvesting on stand structure, biomass production and mechanical stability of reeds has been described elsewhere

Table 1. Limnological features of Lake Constance Untersee.

Location	8°51'37" - 9°08'23" Long. 47°38'45" - 47°44'17" n. Lat.	
total water surface (at m.w.l. = 395.11 m a.s.l.)		61.8 km^2
littoral water surface (0-5 m below m.w.l.)		24.7 km^2
eulittoral area (394.0 - 396.0 m a.s.l.): area		10.2 km^2
	mean width	143 m
	mean slope	0.80°
mean water level (mean of the period 1887-1987)		395.11 m a.s.l.
mean high water level (June/July) (mean of the period 1887-1987)		396.33 m.a.s.l.
low water level (Jan/Febr) (mean of the period 1887-1987)		394.30 m.a.s.l.
trophic level: eutrophic:	1960	c. 45µg L^{-1} P_{diss}
	1973-1979	c. 90-100 µg L^{-1} P_{diss}
	1988-1991	c. 45-65 µg L^{-1} P_{diss}

(Ostendorp 1987; 1995). This study was conducted to determine if winter mowing and burning is an effective strategy to influence the nutrient economy of lakeside reed beds within a limited observation period of four years.

Study area, materials and methods

Lake Constance-Untersee is the western part of the Lake Constance system (SW-Germany, Switzerland, Austria), a shallow, eutrophic lake with broad shelves. It has extensive reed belts (mainly *Phragmites australis* (Cav.) Trin. ex Steud., Poaceae) covering 31 % of the eulittoral area, and 54 % of the total shore length (German territory only) (Ostendorp 1991). The sublittoral zone is covered with submerged macrophytes, *i.e., Chara* spp., *Potamogeton* spp., and filamentous algae. Table 1 gives a brief overview of some important limnological characteristics of the lake.

The littoral sediments consist of post-glacial lake marl and onkolithic carbonates, and, to a minor part, of late-glacial clays and deltaic sands of small rivers. Within the reed beds these sediments are overlaid with *Phragmites*- and *Carex*-peat, which is less than one hundred years old. A detailed description of eulittoral sediments and a model of within-reed bed sedimentation is given by Ostendorp (1992).

Full scale mowing experiments were conducted between 1979 and 1984. The mowing was done by different types of caterpillar vessels with an interchangeable mowing and chaffing device in the front. The chaffed straw and litter was removed from the bed either by hand or by a machine that sucked the material from the roller and blew it into a container. In some cases the reeds were burnt down, leaving the ash on the ground. The work done in winter when the water level was low and the ground frozen.

Three experimental areas were monitored (Horn, Moos, and Hegne, Fig. 1). Each area was divided into one untreated reference field, and two winter-harvested or burnt fields. All sampling was performed along cross-shore transects extending from the lakeside reed front to the mixed *Phragmites-Carex-Phalaris* zone at the landward edge. Each reference and experimental field was represented by one transect.

The sediment top layer (0 to 2.5 cm depth) was sampled in winter using plastic tubes (Ø = 4 cm) after the coarse *Phragmites* litter was removed. The samples were oven dried (70 °C), homogenized in a pebble mill and sieved through a 2 mm mesh-size sieve. The fine fraction was analyzed for organic matter (OM), total nitrogen (N_t), and total phosphorus (P_t) (see below). The dry matter content of a sediment core of 4 cm diameter and 2.5 cm thickness was used to calculate the bulk density (BD, kg dry matter per m^2 in a sediment surface layer of 1 cm thickness).

Water samples were taken in the reed belt from the water surface and from the bottom water layer (approximately 5 cm above ground) by means of a suction-apparatus with a 0.2 mm mesh filter at the intake. The samples were stored dark and cold, and were immediately processed in the laboratory for

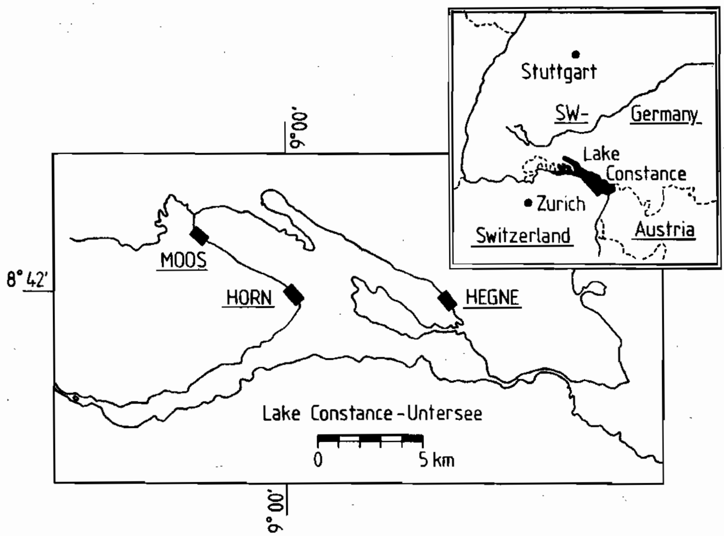

Fig. 1. Position of the experimental areas Horn, Moos and Hegne on the shore of Lake Constance-Untersee.

pH, pe_7, electrical conductivity (κ_{20}), PO_4-P (SRP, molybdenum reactive phosphate), NO_3-N, and dissolved Si. Sampling was done using a canoe to minimize disturbance to the stratified littoral water body.

The influence of winter reed harvesting on the decay rates of the *Phragmites* litter was tested using a litter bag assay. The nylon bags (25 x 35 cm, mesh size 1.6 mm) were filled with approximately 200 g oven dried (70 °C) pieces of dead *Phragmites* stem material (no leaf sheaths) that was harvested in the winter of the same year. The bags were exposed onto the mineral sediment or imbedded in the *in situ* litter layer along the transects for 219 to 227 days (April to November/December). After retrieving the bags, the contents were cleaned of foreign matter (roots, snails, beetles etc.). The litter was suspended in deionized water, and gently washed over a 1 mm sieve. The residue was analyzed for dry matter (70 °C), OM, N_t and P_t. The mean decay rate refers to a linear decay model (mg dry matter loss per day and g of the original dry matter during exposition time). The "decay" comprised decomposition and mineralization of the organic material to soluble and volatile compounds, as well as loss of crushed, small sized particles.

The sedimentation rates were measured along six transects on three harvested and three unharvested test fields, using sedimentation tubes as described in Ostendorp (1992). The tubes were installed in early spring, before the summer flooding began, and recovered in late autumn. The contents were oven dried (70 °C), and analyzed for OM. The sedimentation rate is given as dry matter (and OM) per square meter and year. Note that the settling of particles takes place only during the submergence period at the sampling site, which depends on the position of the tubes along the transect. Hence, the sedimentation rate is high at the lakeside edge, and low at the inland side.

The analytical procedures were as follows:

- organic matter (OM): loss on ignition (560 °C, 8 h) in a muffle furnace
- total phosphorus (P_t): photometrically as molybdenum complex with ascorbic acid as a

reduction reagent (DEV 1983) after H_2SO_4/H_2O_2 digestion of the ash

- soluble reactive phosphorus (PO_4-P): in 0.45 µm-filtered water photometrically as molybdenum complex with ascorbic acid as a reduction reagent (DEV 1983)
- total nitrogen (N_t): photometrically as NH_4^+ (indophenole blue method) (DEV 1983) after Kjeldahl digestion without a reduction reagent
- ammonia (NH_4-N): in 0.45 µm-filtered water photometrically with the indophenole blue method (DEV 1983)
- nitrate (NO_3-N): in 0.45 µm-filtered water with a Technicon II Autoanalyzer
- dissolved silica (Si): in 0.45 µm filtered water with a Technicon II Autoanalyzer
- chemical oxygen demand (COD): in 0.45 µm filtered water according to DEV 1981
- dissolved oxygen (O_2): Winkler-method (DEV 1984)
- pH: potentiometrically in the dark sample near 20 °C
- pe_7 (pe_7 = 0.5 rH - pH + 7, redox milieu, see Frevert 1983): Ag°; AgJ (1 to 3 mol L^{-1} KJ)/glass/Pt probe with a pH-probe as a reference
- specific conductivity (κ_{20}): conductivity cell with temperature compensation (see DEV 1985)

Concentrations in water are given as mg L^{-1}, and OM and nutrient contents in the sediment as m/m (mass/mass) concentrations [mg g^{-1}, µg g^{-1} dry matter], as well as m/v (mass/volume) concentrations (grams per m^2 in a layer of 1 cm thickness [g m^{-2} cm^{-1}]). m/v concentrations were computed from the m/m concentrations and the bulk density; they are marked with an "*".

Results

Organic matter and nutrient pools in the reed beds

An average m^2 of fringing reed stand at Lake Constance-Untersee contained 25.1 kg OM (= 100 %), 2.08 kg N_t (= 100 %), and 54.4 g P_t (= 100 %) (data from dead reed stalks, litter, top and deeper sediment layers up to a depth of 0.6 m [*i.e.*, mean depth boundary of the *Phragmites* horizontal rhizome layer]) (Fig. 2). These figures represent the means from lakeside and landward stands along a cross-shore transect. Fig. 2 shows how these pools are apportioned to the different compartments of the stand.

The main part (74 % of OM, 96 % of N_t, and 89 % of P_t) is contained in the mineral sediment and in the organic top layer of approximately 10 cm thickness, whereas the living rhizomes contribute only 13 % of the OM, 2 % of the N_t, and 7 % of the P_t.

The average quantity of nutrients in the interstitial water amounts to 0.07 g NO_3-N, 2.42 g NH_4-N, and 0.20 g PO_4-P in a sediment column of 1 m^2 x 0.6 m depth (362 L pore water per m^3 bulk sediment). The nutrient pool in the overlying littoral water is not considered, because the figures reported here refer to the situation in winter, when the lake level has dropped down (cf. Table 1).

By harvesting an "average" reed stand in winter approximately 90 % of the *Phragmites* stem crop, approximately 50 % of the total leaf biomass, and about 50 % (first harvest) to 20 % (second and following harvests) of the litter could be removed. These figures are highly variable. They depend on the type of mowing machine and cutting and chaffing device. The elimination rate of stem and leaf material is high when the ground is frozen, but litter and peat stock are not greatly affected. Otherwise, the aboveground biomass export is reduced, but the top layer of the litter and the peat stratum can be caught by the chaffing device of the mowing machine. The amount of harvested leaf material is relatively low because the leaf shedding takes place in November/December, usually before the reed harvesting operations begin.

The following reduction of total pools by a single harvesting operation was calculated based on these figures:

OM :- 4.2 % (*i.e.*, 1.05 kg OM m^{-2})
N_t :- 0.4 % (*i.e.*, 7.6 g N_t m^{-2})
P_t: - 0.9 % (*i.e.*, 0.5 g P_t m^{-2})

The percentages of reduction change depending on what is taken as the pool. With the standing crop, the litter, the peat layer and the organic sediment layer as the 100 % basis, the corresponding figures amount to 16.4 %, 3.3 %, and 2.3 %. These esti-

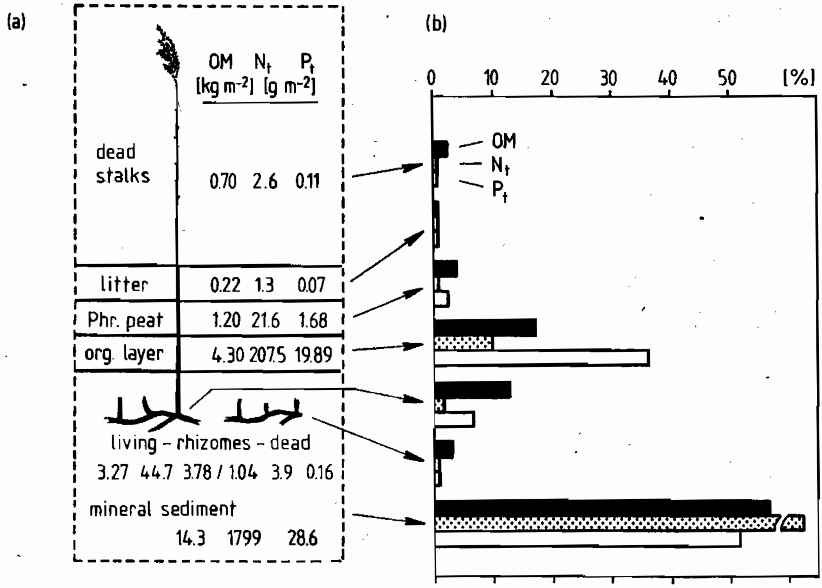

Fig. 2. Pool sizes of organic matter (OM), total nitrogen (N_t) and total phosphorus (P_t) in a reed bed of 1 m² size and 0.6 m depth below ground; data are means of untreated reedbeds in winter (dead *Phragmites* stems, dead biomass of leaves added to the litter layer), (a) - pool sizes in kg m^{-2} (OM), and g m^{-2} (N_t, P_t), (b) - percentages of the total pool (=100 %) in each layer.

mations, however, refer to total OM and element concentrations, and not to mobile and exchangeable fractions that can easily be processed by microorganisms and plant roots.

Hydrochemistry of within-reed water bodies

Water samples were taken from the surficial water layer (= SWL) and from the near bottom water body (= BWL; approximately 5 cm above ground) during summer, when the reed belt was flooded to a depth of 30 to 130 cm. The SWL differed clearly from the BWL with respect to nearly all parameters (Table 2). The BWL expresses the chemical and metabolic processes at the water-sediment interface. Oxygen was depleted due to microbial decomposition of *Phragmites* litter and other kinds of detritus, producing soluble organic substances (high COD), of which some were reduced (somewhat lower pe_7). Ions were released during decomposition (increased κ_{20}), among others PO_4-P and Si. Inorganic nitrogen species, however, seemed to be absorbed by the sediment, as their concentration in the BWL was lower than in the SWL. General aspects of the limnochemistry of within reed water bodies are discussed elsewhere (Ostendorp, in prep.).

Table 3 includes the differences of hydrochemical features of the BWL between harvested and unharvested reeds. The temperature of the BWL differed significantly for all pairs (treated stands/controls), but these differences must have other causes than winter harvesting of the reed, because in Oberzell and Hegne (B) the BWL of treated fields is colder, and in Moos and Horn (A) it is warmer. Similarly, significant differences in oxygen content, pH, pe_7, NO_3-N in the test fields showed different signs. There is some indication that in winter harvested areas more ions were released than in untreated reference areas (increased κ_{20}). The increase in conductivity is to a

Table 2. Hydrochemistry of the surficial water layers and of the bottom water layers of 4 pairs of treated and untreated reed belts in Lake Constance-Untersee (all data pooled; means ± 1 Std.Dev.; test statistics: paired t-test, n.s. - not significant at the $\alpha = 0.05$ level, *= $\alpha < 0.05$, **= $\alpha < 0.01$, *** = $\alpha < 0.001$, **** = $\alpha < 0.0001$).

		n	Surface water		Bottom water
Temperature	[°C]	61	21.7 ± 1.9	****	21.0 ± 1.7
Oxygen	[mg O_2 L^{-1}]	47	8.14 ± 2.01	****	2.46 ± 2.63
pH		61	8.33 ± 0.30	****	7.82 ± 0.27
pe_7		61	6.28 ± 0.59	****	6.03 ± 0.51
κ_{20}	[µS cm^{-1}]	61	244 ± 14	****	276 ± 45
COD	[mg O_2 L^{-1}]	16	6.8 ± 1.6	**	11.0 ± 5.9
PO_4-P	[µg L^{-1}]	61	4 ± 4	****	57 ± 76
NO_3-N	[µg L^{-1}]	61	84 ± 43	***	56 ± 57
NH_4-N	[µgL^{-1}]	32	31 ± 24	n.s.	28 ± 20
Si	[mg L^{-1}]	60	0.47 ± 0.26	****	2.31 ± 2.45

great part attributed to a release of Ca^{2+} and HCO_3^-, since these two ion species were found to be significantly correlated with ($\alpha < 0.05$, data from Banoub 1975). The mean PO_4-P concentrations in the BWL of untreated controls was always low. In mown areas they were significantly higher in some cases.

In summary, there were no obvious differences in the BWL between winter harvested and untreated reed belts and it seems that very local circumstances influence the hydrochemical properties more than the treatment.

Decay rates of the Phragmites *litter*

The results of the litter bag decay experiments are shown in Fig. 3. Evidently, the daily decay rates depended on the distance from the lakeside reed front, as well as on the treatment, being highest near the open lake, where the bags were agitated by waves, and decreasing towards the landward edge.

Litter bags were exposed in the landward part of harvested and untreated reeds in a subsequent series of experiments, to avoid dry matter loss from the bags by wave action and strong currents. Exactly the same position relative to mean water level was chosen in each pair. A total of 10 pairs (with two triplicates each) was investigated. The mean daily decay rate for the treated and reference reed beds was 0.95 ± 0.14, and 0.86 ± 0.22, respectively [mg g^{-1} d^{-1}] (means ± SD, n = 12, pairs shown in Fig. 3 included). There was a tendency for greater rates in winter harvested reed beds, but significance could not be established (paired t-test: $\alpha = 0.107$, Wilcoxon rank test: $\alpha = 0.084$, n = 12). Again, local differences influence the mean daily decomposition rate to a greater degree than the winter harvesting treatment.

Deposition rates of solid matter

The deposition rates of fine sized matter depend greatly on the elevation of the opening of the sedimentation tubes relative to the mean water level (Ostendorp 1992). The rates were highest at the lakeward border (*i.e.*, below mean water level, long period of submergence with a high water column, on average, and high intensity of wave action and currents), and lowest at the landward edge of the reed beds (*i.e.*, above mean water level, short period of submergence with only a low water column, and only local currents) (Fig. 4).

The data sets were fit to the regression model $\ln Y = a + b \ln X$, where Y = elevation of the opening of the sedimentation tube [m a.s.l.] (mean water level: 395.11 m.a.s.l., see Table 1), Y = dry matter (and organic matter, respectively) [kg m^{-2} a^{-1}]. The following regression curves were obtained (Fig. 4):

(a) dry matter deposition
winter harvested (coefficients a_1, b_1):
$\ln Y = 17{,}444.7 - 2917 \ln X$, n = 18,
$r = 0.855$, $\alpha < 0.001$
untreated (coefficients a_2, b_2):
$\ln Y = 16{,}767.7 - 2804 \ln X$, n = 17,
$r = 0.868$, $\alpha < 0.001$

Table 3. Limnochemical parameters in the bottom water layer of treated and untreated reed belts in Lake Constânce-Untersee (means ± SDs; test statistics: unpaired t-test in case of insignificant differences in variances, U-test; for symbols see Table 2).

	OBERZELL treated/ untreated (n = 7/6)	MOOS treated/ untreated (n = 6/5)	HORN (A) (*) treated/ untreated (n = 6/7)	HORN (B) (*) treated/ untreated (n = 7/7)	HEGNE (B) (*) treated/ untreated (n = 24/24) (**)	HEGNE (B) (*) treated/ untreated (n = 7/6)
Temperature [°C]	19.7 ± 0.5 (*) 20.5 ± 0.8	17.3 ± 0.6 * 16.1 ± 0.8	17.4 ± 0.7 ** 15.9 ± 0.3	-	21.0 ± 1.0 **** 22.3 ± 0.9	-
Oxygen [mg O_2L^{-1}]	9.74 ± 0.93 n.s 8.83 ± 1.72	7.34 ± 1.91 ** 2.61 ± 2.66	7.39 ± 2.24 n.s. 8.06 ± 1.06	-	1.31 ± 1.90 - 3.51 ± 2.80	
pH	8.03 ± 0.10 n.s. 8.09 ± 0.17	8.06 ± 0.17 * 7.70 ± 0.25	8.11 ± 0.25 n.s. 8.05 ± 0.14	-	7.64 ± 0.19 *** 7.87 ± 0.24	
pe_7	5.86 ± 0.11 **** 6.65 ± 0.14	6.20 ± 0.38 n.s. 6.00 ± 0.12	6.82 ± 0.23 ** 6.29 ± 0.12	-	5.73 ± 0.41 ** 6.18 ± 0.46	
κ_{20} [µS cm^{-1}]	236 ± 4 n.s. 236 ± 4	267 ± 4 n.s. 273 ± 13	237 ± 4 n.s. 237 ± 2	268 ± 61 n.s. 226 ± 29	320 ± 42 **** 254 ± 9	249 ± 21 * 215 ± 24
COD [mg O_2L^{-1}]	–	–	–	–	15.7 ± 4.3 *** 6.3 ± 2.3	-
PO_4-P [mg L^{-1}]	9 ± 2 n.s. 15 ± 6	21 ± 2 n.s. 20 ± 2	6 ± 4 n.s. 5 ± 2	89 ± 110 n.s. 12 ± 3	129 ± 80 **** 13 ± 14	69 ± 51 n.s. 30 ± 10
NO_3-N [mg L^{-1}]	53 ± 18 ** 87 ± 15	377 ± 31 * 225 ± 104	182 ± 16 ** 222 ± 8	89 ± 92 n.s. 76 ± 93	38 ± 53 * 45 ± 31	0 ± 0 * 7 ± 5
NH_4-N [µg L^{-1}]	-	-	-	-	17 ± 10 ** 39 ± 23	-
Si [mg L^{-1}]	0.38 ± 0.07 n.s. 0.34 ± 0.07	0.68 ± 0.15 (*) 0.85 ± 0.19	0.27 ± 0.07 n.s. 0.27 ± 0.02	2.42 ± 2.15 (*) 0.74 ± 1.05	4.88 ± 2.16 **** 0.95 ± 0.45	0.71 ± 0.42 n.s. 0.84 ± 0.26

(*) (A), (B): sampling series in subsequent years at the same locations
(**) n = 8 for COD, n = 16 for NH_4-N

(b) organic matter deposition

winter harvested (coefficients a_1, b_1):

$\ln Y = 11{,}568.7 - 1935 \ln X$, $n = 18$, $r = 0.799$, $\alpha < 0.001$

untreated (coefficients a_2, b_2):

$\ln Y = 12{,}925.8 - 2162 \ln X$, $n = 17$, $r = 0.847$, $\alpha < 0.001$

The differences between the coefficients a_1 and a_2, and b_1 and b_2, respectively, were tested for significance using the SAS 6.03 Proc Syslin. The coefficients were tested simultaneously (*i.e.*, for the regression curve as a total), and separately. No one test yielded significant differences, either for the

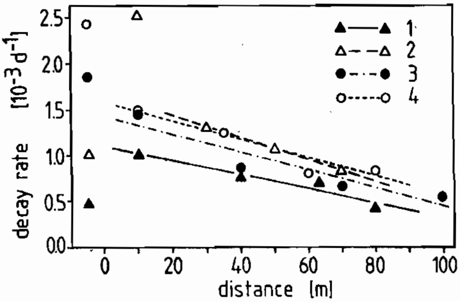

Fig. 3. Dependence of the decay rates of *Phragmites* stem material (litter bag method) on the distance from the lakeside reed border (1 - Hegne, reference, 2 - Hegne, winter harvested, 3 - Horn, reference, 4 - Horn, winter harvested).

dry matter deposition, nor for the organic matter deposition. Hence, it is concluded that deposition rate within reed beds is not significantly influenced by the winter harvesting treatment.

Distribution of OM, N_t and P_t in cross shore transects

The OM and nutrient content in the sediment matter was determined along cross shore transects which ran from the lakeside edge (0 m in Fig. 5 and 6) through the monospecific reed bed to the landside border where *Phalaris arundinacea* and *Carex* spp. dominated the vegetation cover, and *Phragmites australis* became subdominant. Two examples are in Figs. 5 and 6.

The topography is, in these cases, characterized by a steep erosion scarp at the lakeside edge. On the landward side the bottom surface rises gently (Fig. 5a, 6a). Submergence normally begins in the last days of April (Moos-harvested), or at the end of May (Moos-Ref), and lasts for 88 to 150 days. From the mid of September (Moos-Ref) and the mid of October (Moos-harvested) the sediment surface runs dry. However, groundwater soaks into the reeds and wets the surficial sediment layers thoroughly for the rest of the year.

The standing crop of the monospecific reed stands was about 1 and 2 kg dry matter per m^{-2} (Fig. 5b, 6b). At the landward edge, the *Phragmites*

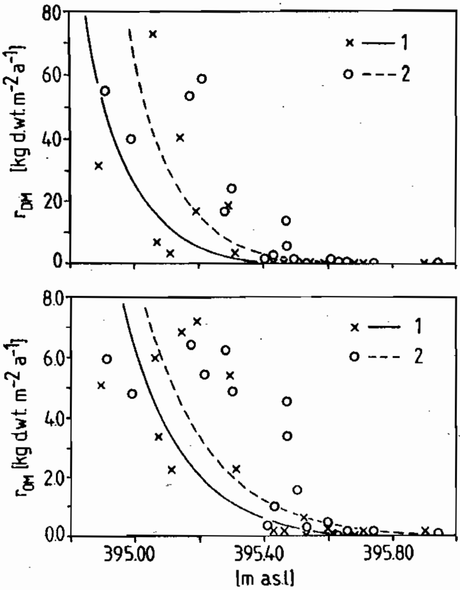

Fig. 4. Yearly rates of dry matter (r_{DM}) and organic matter deposition (r_{OM}) in untreated (1) and winter harvested reeds (2) as a function of sediment surface position relative to the mean water level (395.11 m a.s.l.) (data from Horn, Moos, and Hegne pooled; see text for regression coefficients).

biomass gradually dropped down to values of approximately 0.5 kg dry matter per m^{-2} or less. The biomass of accompanying wetland plants was not measured.

The sediment consisted of silty and sandy lake marl covered with reed and sedge peat, and with strongly disintegrated litter at the top. The fresh and weakly fragmented litter was not included into the sediment sample.

Fig. 5c and 6c show the bulk density of the 0-2.5 cm sediment layer. It is well correlated with the content of OM:

$$BD = 7.80 - 0.0116\,OM\ ;\ r = 0.833\ ;\ n = 81$$

(all data pooled)
BD [kg dry matter per m^{-2} cm^{-1}],
OM [mg g^{-1} dry matter]

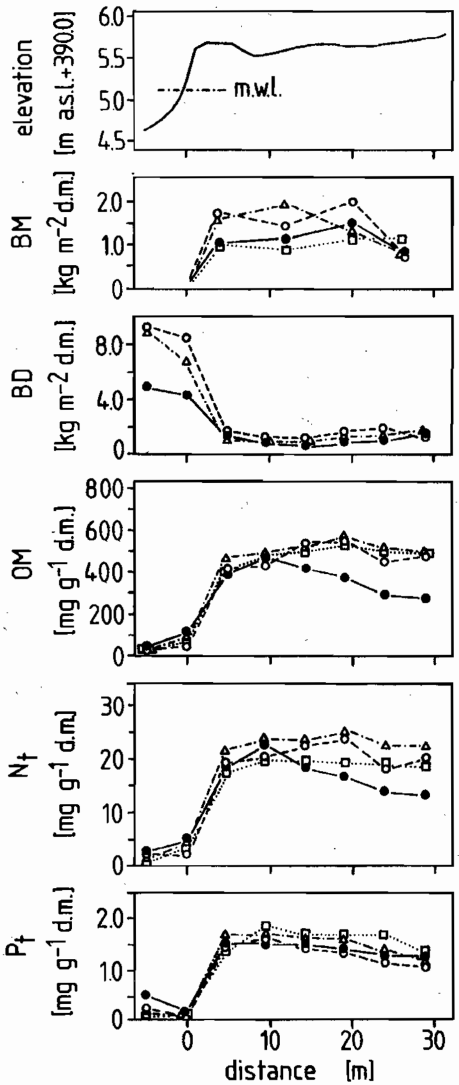

Fig. 5. Cross shore distribution of bulk density (BD), organic matter (OM), total nitrogen (N_t), and total phosphorus (P_t) along the transect Moos-reference; Symbols: filled circles = before the first winter harvesting, open circles, triangles and squares are after the first, second, and third winter harvesting operation, respectively; m.w.l. = mean water level; 0 m = lakeside reed front.

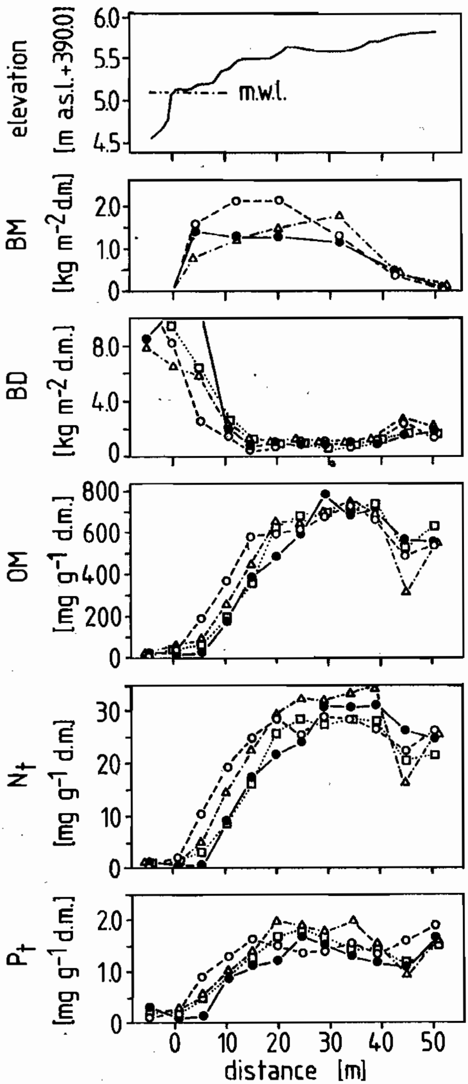

Fig. 6. Cross shore distribution of bulk density (BD), organie matter (OM), total nitrogen (N_t), and total phosphorus (P_t) along the transect Moos-harvested. Symbols: filled circles = before the first winter harvesting, open circles, triangles and squares are after the first, second, and third winter harvesting operation, respectively; m.w.l. - mean water level; 0 m - lakeside reed front.

The OM and nutrient content in terms of m/m concentrations were multiplied with the bulk density to yield the OM and nutrient amount per m^2 in a layer of 1 cm thickness (OM*, N_t^*, P_t^*) (see next section for results).

The OM content of the surficial sediment layer was low at the lakeside edge (Fig. 5d, 6d) due to local erosion or winnowing the particulate matter by waves and breakers. Wave action and littoral currents are slowed down in the landward parts of the reed belt (Meissner and Ostendorp 1988). Thus, the particulate organic matter can settle down and decay without cycles of resuspension, winnowing and redeposition (Ostendorp 1992). Nitrogen and phosphorus are closely correlated with OM. The relationship is well fitted by the regression model $y = a_1 x + a_2 x^2$:

$N_t = 49.2 \cdot 10^{-3}$ OM - $10.63 \cdot 10^{-6}$ OM^2; n = 81, R = 0.985

$P_t = 4.87 \cdot 10^{-3}$ OM - $3.79 \cdot 10^{-6}$ OM^2; n = 81, R = 0.935

(all data pooled, N_t [mg g^{-1} kg dry matter], OM [mg g^{-1} dry matter]).

It is therefore reasonable that the graphs for the nutrient concentrations resemble those for the OM (Fig. 5e and f, 6e and f).

OM and nutrient budget of the sediment top layer

The data sets of a total of 404 sediment samples from 9 transects (6 treated, 3 untreated, monitored for up to 4 years) were arranged to yield six groups:

U1/U2: untreated in the first year of observation (U1) / untreated in the following year (U2): 6 pairs of transects with a total 56 data pairs for BD, OM, OM*, N_t, N_t^*, P_t, and P_t^*, respectively,

U1/M1: untreated in the first year (U1) / mown in winter, and sampled after the first summer flooding had passed (M1): 4 pairs of transects with a total of 43 data pairs,

U1/B1: untreated in the first year (U1) / burnt in winter, and sampled after the first summer flooding period (B1): 2 pairs of transects with 19 data pairs

U1/M2: untreated in the first year (U1) / mown in the next two winters, and sampled at the end of the summer flooding period following the second treatment (M2): 5 pairs of transects with 56 data pairs

U1/M3: untreated in the first year (U1) / mown in three succeeding winters, and sampled at the end of the summer flooding period following the third treatment (M3): 2 pairs of transects with 23 data pairs

M/U1: mown in one or two succeeding winters, sampled at the end of the summer flooding period following the last treatment (M) / untreated in the next winter, and sampled after the summer flooding period (U1): 4 pairs of transects with 45 data pairs.

Each data pair derived from the same location. So, within each group the pairs were tested for significance of differences using the paired t-test. Note, that the U1's comprise different data sets for the six groups. The results are shown in Table 4 and summarized below.

(1) The comparison of U1/U2 yielded a significant change in only one case (ΔOM = +29 mg g^{-1}, *i.e.*, +8.4 % of the initial mean value in U1). Most other changes are positive, but do not exceed 6 % of the corresponding initial values. The results show that in unaffected reed beds the nutrient content (m/m as well as m/v-concentrations) of the sediment top layer remained constant or increased insignificantly over a number of years.

(2) After one mowing treatment, the changes of most parameters are insignificantly different from zero (comparison U1/M1). Again, the changes of OM and N_t were positive, but P_t and P_t^* decreased. ΔOM = +5.5 %, the only significant case, was nearly as great as in U1/U2.

(3) After one burning treatment in late winter (comparison U1/B1), the data showed a weak tendency for a decrease of m/m-concentrations, of which ΔN_t = -15.8 % is significant.

(4) After the reeds had been mown two times (comparison U1/M2) most parameters have changed significantly. The bulk density increased by 26%. This corresponds with the decrease in OM, because both variables are highly negatively correlated:

Table 4. Sediment chemistry of experimental reed bed areas. Data are grouped to give the pairs U1/U2,...,M/U1 (see text for explanations). Mean absolute and percent differences in bulk density of the sediment top layer (BD), organic matter (OM, OM*), total nitrogen (N_t, N_t*), and total phosphorus (P_t, P_t*) are displayed together with symbols of significance (see Table 2); test statistics: paired t-test; signs: +, -: increase or decrease compared to U1,..., M; m/v concentrations are labeled with an "*".

	U1/U2	U1/M1	U1/B1	U1/M2	U1/M3	M/U1
BD [kg m^{-2} cm^{-1}]	-0.08 (-3.6%) n = 51, n.s.	-0.20 (-10.4%) n = 43, n.s.	-0.13 (-3.9%) n = 19, n.s.	+0.63 (+25.7%) n = 55, **	+0.16 (+4.3%) n = 23, n.s.	-0.24 (-9.1%) n = 45, (*)
OM [mg g^{-1}]	+29 (+8.4 %) n = 51, *	+25 (+5.5%) n = 43, (*)	-14 (-5.1%) n = 19, n.s.	-63 (-16.2%) n = 55, **	-13 (-4.3%) n = 23, n.s.	+ 28 (+ 8.5%) n = 45, **
OM* [g m^{-2} cm^{-1}]	+ 4 (+ 0.8%) n = 51, n.s.	+19 (+ 4.1%) n = 43, n.s.	+11 (+2.2%) n = 19, n.s.	+19 (+4.3%) n = 55, n.s.	+18 (+3.7%) n = 23, n.s.	- 52 (-12.5%) n = 45, *
N_t +0.19 [mg g^{-1}]	+0.6 (+5.6%) n = 51, n.s.	-1.8 (+3.0%) n = 43, n.s.	-2.3 (-15.8%) n = 18, *	-1.1 (-13.6%) n - 54, **	- 0.5 (-9.0%) n = 23, n.s.	(-3.6%) n = 44, n.s.
N_t* [g m^{-2} cm^{-1}]	-01 (-0.3%) n = 51, n.s.	+0.6 (+2.7%) n = 43, n.s.	-0.2 (-0.8%) n = 18, n.s.	+2.6 (+12.8%) n = 54, *	+0.5 (+2.6%) n = 23, n.s.	-2.9 (-14.6%) n = 44, **
P_t [mg g^{-1}]	+0.04 (+3.7%) n = 51, n.s.	-0.07 (-5.3%) n = 33, n.s.	-0.09 (-6.7%) n = 18, n.s.	-0.31 (-23.3%) n = 46, ***	-0.26 (-22.0%) n = 23, (*)	+0.17 (+16.7%) n = 40, ***
P_t* [g m^{-2} cm^{-1}]	+0.03 (+1.5% n = 51, n.s.	-0.13 (-6.4%) n= 33, n.s.	+0.12 (+3.2%) n = 18, n.s.	+0.07 (+2.6%) n = 46, n.s.	-0.54 (-17.5%) n = 23, (*)	+0.16 (+7.7%) n = 40, n.s.

U1 : $BD = 106.7\ OM^{-0.751}$, n = 53 , r = 0.944
M2 : $BD = 104.0\ OM^{-0.732}$, n = 53 , r = 0.871
Both regressions do not differ significantly on the $\alpha = 0.05$ level. Thus, the decrease in OM is the main reason for the increase in BD. OM, N_t and P_t decreased significantly, whereas OM*, N_t^* and P_t^* showed a slight increase, due to the increase in BD.

(5) After three consecutive treatments (comparison U1/M3) most m/m-differences followed the same decreasing trend as in U1/M2. However, the differences were smaller, and, except ΔP_t, not significant. The m/v-concentrations increased, with the exception of P_t^*.

(6) After the mowing and burning management had stopped (comparison M/U1), OM increased, and consequently the BD dropped down. The N_t concentrations decreased, but P_t, and P_t^* increased. The differences were significant only in some cases.

In a subsequent test, the data sets of each transect were split into a "lakeside" and into a "landside" subset. This was done because these two sections are influenced differently by waves and washes. Comparisons were made using the same groups as listed above. The splitting did not increase the share of significant changes (11 out of 42 in the "lakeward" subset, and 9 out of 42 in the "landward subset"). In only one case, the changes in the two sections showed opposite signs, that were significant, both. This consequently led to an insignificant change for the total transect. In all other cases the low share of significant comparisons (16 out of 42 combinations, if each transect is regarded as a total) was not caused by changes with opposite

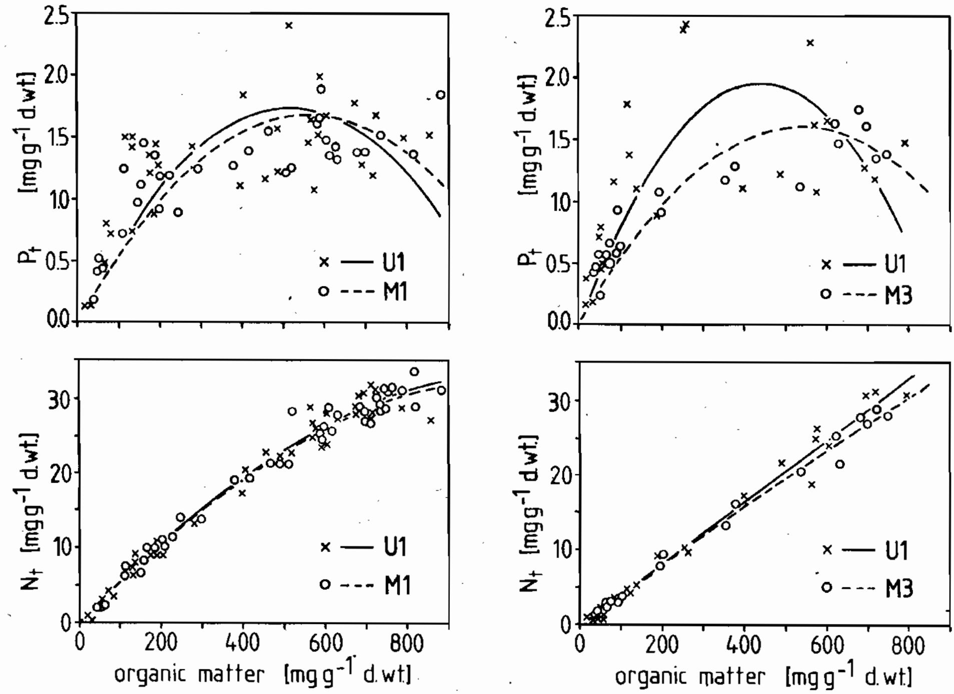

Fig. 7. Regression curves of $N_t = N_t$ (OM) and $P_t = P_t$ (OM) for the pairs U1/M1 (untreated/mown fields) and U1/M3 (untreated, 3 mowing operations); the regression model was E $\{N_t, P_t\}$ = a OM + b OM² (see text for explanations).

signs in the lakeside, and landside areas of the test fields, respectively.

OM-independent changes of N_t and P_t

N_t and P_t are closely correlated with the OM concentrations in the sediment top layer. The data pairs were well fitted by the regression model N_t (and P_t, respectively) = a OM + b OM² (Ostendorp 1992); this means that N_t and P_t change parallel to changes in OM. The question was to be answered, whether the changes in N_t and P_t during the treatments can be explained by OM changes alone, or, whether the nutrient concentrations fluctuate to some degree independently from OM. If the first case is true, the coefficients a_1, a_2, and b_1 b_2, respectively, should be the same for the treatments 1 and 2 (H_0). In the second case, a_1, a_2 and/or b_1, b_2 should be significantly different, depending on treatment (H_1).

The data were grouped as described in the previous section, and regressions were computed for each data set U1, U2, ..., M, and U1 separately. The correlation coefficients were always $R > 0.96$ ($\alpha < 0.001$) for $N_t = N_t$(OM), and usually $R > 0.49$ ($\alpha < 0.001$) for $P_t = P_t$ (OM). Coefficient a was significant in all cases on the $\alpha < 0.001$ level (N_t, and P_t), and b was significant ($\alpha < 0.001$) in 8 out of 12 cases for N_t, and in 11 out of 12 cases for P_t, respectively. H_0 was tested for each pair U1/U2, ..., M/U1 using the SAS 6.03 Proc Syslin. The coefficients were tested simultaneously as well as separately.

No significant differences in a, nor b, nor for both coefficients tested simultaneously, were observed for the pair U1/U2 (no treatment) ($\alpha >$

0.05). Changes in N_t and P_t are, therefore, mainly due to changes in OM. The same was yielded for U1/M1 (winter mowing): N_t (OM) (and P_t (OM), respectively) can be described by the same function in both treatments. There is no indication that N_t and P_t change independently from OM (Fig. 7, left).

When the reeds were burnt in winter (U1/B1), the regression curves N_t(OM) differed significantly for this pair ($\alpha < 0.001$). In the landward section of the test field, the organic sediment top layer was lower in N_t after burning than before. P_t regression equations did not differ significantly.

After repeated winter harvesting (U1/M2) the differences between the regression curves were not significant. However, when the treatment had been continued for three times, the regression curves N_t(OM), and P_t (OM) showed a feebly significant difference ($\alpha = 0.02$, and $\alpha = 0.066$, respectively) (Fig. 7, right). A clear tendency for lower N_t concentrations for a given OM content was found in the landward section of the transect (significant difference of the regression curves $\alpha = 0.005$, landside data pairs only), and a weak tendency ($\alpha = 0.065$) for lower P_t values in the lakeside section. This means that the decrease of N_t by -9 %, and P_t by –22 %, on average, was not only the consequence of a lowering in OM (-13 %), but also to low N_+ and P_+ with respect to organic matter.

When winter harvested reeds were left untreated (comparison M/U1), the corresponding regression curves of N_t and P_t were found to be significantly different ($\alpha < 0.0001$, and $\alpha < 0.05$, respectively). The N_t concentration was lower for a given OM content (in the lakeward as well as in the landward section), but the P_t concentration was higher. Again, this indicates that an OM independent change in N_t and P_t in the sediment top layer took place. In this case, however, N_t decreased, whereas P_t increased.

Discussion

At the first glance, it seems possible that the export of organic matter and nutrients by winter mowing or burning of littoral reeds might reduce the nutrient content of the sediments. There is, however, some debate on the manner how this can take place and its significance (Klötzli and Züst 1973, Schröder 1979, 1987: pp. 67-70, Hansson and Graneli 1984, Hammer 1985). With this background in mind, full scale mowing and burning experiments were performed at Lake Constance-Untersee, and the changes of sediment and water chemistry were monitored for up to four years.

The potential effect of a single mowing or burning treatment can be estimated by comparing the total OM and nutrient pool to the corresponding amounts that can be removed from the beds. In wintertime, when harvesting and burning are performed, only a small part of the pool (*i.e.*, 13 % of the OM, 2 % of the N_t, and 7 % of the P_t) is bound to the living phytomass. Similar figures were obtained for a *Betula-Chamaedaphne* carr (Richardson *et al.* 1978: pp. 230-232), and for a *Spartina* marsh (Delaune and Patrick 1980). Under fairly good conditions winter harvesting can reduce the pool (standing crop + litter + peat + organic sediment layer) by -16.4 % of the OM, -3.3 % of N_t, and -2.3 % of P_t. The reduction due to fire management could not be quantified, because its effectiveness strongly depends on weather conditions (*e.g.*, water content of culms and litter, wind direction and velocity). For the experiments with the Lake Constance reed beds, it was assumed, that the OM and N_t removal is nearly equal to the removal by winter harvesting. The difference is that most of the P_t remains in the ash, which is deposited and becomes part of the sediment after a while (Woodmansee and Wallach 1981). Evidently, the calculated impact of a single treatment on total pool size is low, and repeated harvesting or burning operations have to be performed to obtain a measurable effect.

At Lake Constance, reed harvesting was performed in winter, when the culms were dead and low in N_t and P_t (4.1 mg g^{-1} dry matter N_t, 0.18 mg g^{-1} dry matter P_t). If, however, a fully grown reed stand is harvested in summer, then the amount of nutrients exported can be higher. Sieghardt and Maier (1985) estimated that 6.2 - 31.8 g m^{-2} N_t and 0.6 - 3.4 g m^{-2} P_t can be removed by summer mowing of reeds in Neusiedler See. The comparable values at Lake Constance are 3.6 g m^{-2} N_t and 0.11 g m^{-2} P_t (litter not included).

Dead stalk material is poor in nutrients and easily decomposable matter. An efficient allocation mechanism of *Phragmites australis* clones leads to a downward export of nutrient and carbohydrates to the rhizomes in late summer. The efficiency is only 5 - 10 % for C_{org} but 50 - 60 % for N, and approximately 80 % for P (van der Linden 1980, 1986, Esteves 1980, Graneli 1990). The stalk material is rich in refractory organic components, especially lignin (Rodewald-Rudescu 1974: Tab. 52, 53,58,61, Tóth and Szabó 1958). This makes the breakdown rate of dead *Phragmites* material to be 10 to 50 fold lower than in fresh submerged macrophytes (Webster and Benfield 1986). During the decay, refractory components (*e.g.*, lignin) accumulate in the litter, leading to an additional reduction in decay rate (Polunin 1982). This in turn may influence the oxygen consumption rate and the nutrient release or absorption in the water/litter interface.

Comparing the surficial water body (SWL) and the bottom water layer (BWL) (Table 2), there is a clear indication of a release of reduced organic substances, phosphorus, and silica from the litter layer, whereas nitrate and ammonia are removed from the BWL. The high differences in oxygen content point to intensive microbial mineralization processes near the water/litter interface. The SWL represents the free pelagic water body that, during day-time, shifts into the reed belt by a slow temperature induced density current (Meissner and Ostendorp 1988). The outflow of cooler water runs along the ground, transporting the substances released from the litter into the pelagic zone.

The differences of the BWL composition between treated beds and untreated references are significant in many cases for single pairs. No consistent difference could be found, however, when the results of all pairs are taken together. Similar results were reported by Metz (1985: p. 332) in reed beds of Neusiedler See (Austria) harvested in summer. Hansson and Graneli (1984) found pronounced diel variations of water temperature and oxygen saturation in Lake Tåkern reeds (Sweden). Here, the temperature was usually higher in winter harvested reeds during daytime. The corresponding oxygen saturation values were higher on some sampling dates, and lower on others. The PO_4-P concentrations were consistently higher by 5 to 10 mg m^{-3} in unharvested reeds. One source of oxygen input into the reed belts in Lake Constance is the surficial water inflow by the temperature induced density current investigated by Schröder (1973). According to Meissner and Ostendorp (1988) the flow velocity is slightly reduced in mown reeds compared to untreated reference stands, since burning and mowing increases the mean stalk density. Hence, a lower oxygen consumption rate in treated reed beds may be compensated for by a lower oxygen input to the BWL. In conclusion, it seems that the chemical properties of the BWL depend on numerous factors other than treatment.

Water temperature, oxygen saturation and nutrient supply are important factors that control the decomposition of the *Phragmites* litter (Webster and Benfield 1986). Small variations of these physical and chemical properties in the BWL of treated and untreated reeds may affect the litter decay rate. In Lake Constance-Untersee the experiments showed slightly, but not significantly higher rates in harvested reeds than in the reference sites. Similar results were obtained by Bengtsson *et al.* (1983) (cited in Hansson and Graneli 1984: 135). This points to the predominating importance of other factors (microtopography, wetness of the litter layer in spring and autumn, etc.) than winter harvesting or burning.

Sediment formation in lakeside reed beds is the result of autigenic litter production, *in situ* litter decay, and input of allogenic particles (*e.g.*, lake marl and silt sized silicate particles) by littoral currents (Ostendorp 1992). Neither the deposition rate of dry matter nor the rate of organic matter sedimentation from the overlying water was found to be significantly influenced by winter harvesting. If the yearly addition of *Phragmites* litter to the sediment is reduced, the relative proportions of inorganic components should increase, and the m/m concentrations of OM in the sediment top layer would decrease. The same should apply for N_t and P_t, since these elements are highly correlated with OM. The experimental data show a slight but insignificant trend for untreated reed beds to accumulate OM, N_t and P_t in the sediment top layer (U1/U2). After one year's harvesting, this trend is maintained, with the exception of phosphorus. Since the sediment bulk density (BD) is negatively correlated with OM, BD exhibits a slight decrease. After a second and a third winter harvesting, the m/m concentrations declined significantly by 4 - 16 % (OM), 9 - 14 % (N_t), and 22 - 23 % (P_t) of the untreated reference. If the test areas that had been treated several times were left untreated, the m/m concentrations of OM and P_t (but not N_t) increased significantly. The N_t concentrations decreased, probably because the more or less undecomposed *Phragmites* litter from the current year's crop was lower in N_t than the *Phragmites* peat (Ostendorp 1992). The increase of P_t and P_t*, however, cannot be explained on the basis of this argument.

Summarizing these results, it is concluded, that the variability of m/m and m/v concentrations is great. It can be explained only to a small extent by the kind of treatment, since by far not all pairs of data sets show significant differences of means. There is, however, a trend for decreasing m/m concentrations after several years of winter harvesting. This trend is reversed when treated areas are left untreated.

Nitrogen and phosphorus are well correlated with OM. Hence, the changes in N_t and P_t can be explained to a great extent by the changes in OM. An attempt was made to elucidate whether there is also an independent change of N_t and P_t. This was done by testing the coefficients of the regressions $N_t = a\ OM + b\ OM^2$ and $P_t = a\ OM + b\ OM^2$, respectively, for signficant differences (sect. 3.7). Generally, the regression curves were not significantly different. Thus there is no reason to postulate a change in N_t or P_t that is independent from the change in OM between treatments.

Fire treatment, however, caused a significant OM-independent decrease in N_t, especially in the landward section. Presumably, small amounts of partly carbonized *Phragmites* stem material in which N compounds had been volatilized during the fire, were added to the sediment. No significant OM-independent changes in P_t could be observed, *i.e.*, there was no accumulation of P_t in the ash, or in the partly carbonized organic matter of the sediment top layers. This may be attributed to leaching of soluble P compounds by rain or by the littoral water.

After a threefold mowing treatment both nutrients decreased OM independently. This may be due to the fact that the remaining OM in the sediment surface of winter harvested reed beds has been decomposed to more refractory organic compounds. These may contain less N and P compared to a medium disintegrated OM that is intensely colonized with bacteria and fungi. The significant OM independent decrease of N_t, after a winter harvested reed bed is left untreated, is presumably due to "dilution" of the relative N_t rich OM in the sediment top layer by the addition of relative N_t poor *Phragmites* straw. No convincing explanation can be given for the increase of P_t that is also significant.

It is concluded that many succeeding treatments have to be done, to reduce the N_t/OM and P_t/OM relations in the sediment top layers of reed beds.

Conclusions

The impact of winter reed harvesting and burning was investigated at Lake Constance-Untersee with respect to changes of the stand structure, biomass production, and capacity to resist waves and washes (Ostendorp 1987; 1995). The differences between treated and untreated reeds were found to be significant only in the first season following the treatment. The new properties that a mown or burnt reed stand gained remained more or less constant for several periods of treatment. This means that the *Phragmites* clone reacts promptly to disturbance to its internal equilibrium. The changes were reversible when the treatment stopped.

The chemistry of the sediment top layers, however, showed a delayed response. At least two consecutive treatments were necessary before significant changes in the m/m concentrations were observed. Three treatments were required to cause a decrease in N_t and P_t that was independent from a change in OM concentration.

Differences in bottom water chemistry and temperature were small and not usually significant. It is concluded that the quality of microbial decomposition of the remaining *Phragmites* litter and peat did not change much. This is also a valid conclusion for the decomposition of standardized *Phragmites* stem material, because the decay rates did not differ significantly between treatments.

The sediment/bottom water system within lakeside reeds seems to be a well buffered system. It shifts to a relatively nutrient poor state only after many harvesting or burning treatments, if at all. This is understandable, because the litter decays slowly, and the removable dead stalk biomass amounts to only 4.2 % of the total OM pool. Therefore, the benefits of harvesting reeds in winter to prevent reed decline (Klötzli and Züst 1973, Schröder 1987) is dubious. There are, on the other hand, serious disadvantages from this treatment for the mechanical stability of lakeside reeds (Ostendorp 1995), as well as for the avifauna living in them (Ostendorp 1993: 263). Taken all results together, winter reed harvesting and burning is not recommended to improve the functions of lakeside reeds.

Acknowledgments

I appreciate the help of W. Nagl and S. Hochstätter for statistical computations, and of S. Schroeder for editorial comments.

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