

Effect of management on the mechanical stability of lakeside reeds in Lake Constance-Untersee

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Abstract

1. Lakeside *Phragmites australis* reed beds were mown or burnt in winter as a countermeasure against the die-back of reeds in Lake Constance-Untersee.

2. The effect of winter harvesting and burning on the mechanical resistance of reeds against waves and washes was investigated using the *PMR* model. This model postulates that the percentage of mechanically damaged shoots of a reed stand is a monotonically declining function of the mean stem diameter, the relative thickness of the stem wall, the modulus of elasticity, and the shoot density per square metre.

3. Winter harvesting and burning influences the geometric (stem diameter, rel. wall thickness) and the mechanic properties (modulus of elasticity, breaking stress) of culms in each shoot class (primary shoots, secondary shoots, insect infested shoots). The management leads to a shift in stand structure from the dominance of stout primary shoots to the dominance of weaker and thinner secondary shoots. The total shoot density is increased.

4. Mown and burnt reeds exhibit thinner culms, on average, with lower moduli of elasticity at higher shoot densities. Their power of mechanical resistance (*PMR*) is substantially reduced in comparison to the untreated reference. According to this model it is assumed that mown or burnt stands lose significantly more culms and biomass by failing than untreated stands.

5. In Lake Constance-Untersee mechanical factors (waves + washes) are of great significance for the development of the lakeside reed border. In this regard, winter harvesting and burning cannot be recommended as a measure against reed decline.

Keywords: Littoral zone of lakes, *Phragmites australis*, winter mowing and burning, stand structure, mechanical resistance of reeds.

Résumé

1. Les populations du roseau *Phragmites australis* riverain ont été fauchées ou brûlées en hiver pour lutter contre la disparition des roseaux dans le lac mineur de Constance.

2. L'effet du fauchage et du brûlage hivernaux sur la résistance mécanique des roseaux aux vagues et aux remous a été étudié à l'aide du modèle *PRM*. Ce modèle suppose que le pourcentage de rejets endommagés mécaniquement dans une phragmitaie est une fonction monotone décroissante du diamètre moyen des troncs, de l'épaisseur relative de la paroi du tronc, du module d'élasticité et de la densité de rejets par mètre carré.

3. Le fauchage et le brûlage hivernaux influencent les propriétés géométriques (diamètre du tronc, épaisseur relative de la paroi) et mécanique (module d'élasticité, stress du bris) des panicules

dans chaque classe de rejets (rejets primaires, rejets secondaires, rejets infestés par les insectes). La gestion induit un renversement dans la structure de la population, allant de la dominance de vigoureux rejets primaires à celle de rejets secondaires plus faibles et plus minces. La densité totale de rejets augmente.

4. Les roseaux fauchés et brûlés présentent en moyenne des panicules plus fines, avec des modules d'élasticité plus faibles lorsque les densités de rejets sont élevées. Leur pouvoir de résistance mécanique (*PRM*) est réduit de manière substantielle par rapport au témoin non traité. Conformément à ce modèle, nous admettons que les populations fauchées et brûlées perdent significativement plus de panicules et de biomasse que les populations non traitées.

5. Dans le lac mineur de Constance, les facteurs mécaniques (vagues et remous) ont une grande importance pour le développement d'une bordure de roseaux sur les rives. De ce point de vue, le fauchage et le brûlage hivernaux ne peuvent être recommandés pour lutter contre le déclin des roseaux.

INTRODUCTION

A serious decline of lakeside reedbelts (*Phragmites australis* (Cav.) Trin. ex Steud., Poaceae) has been documented in more than 45 Central European lakes (for a review see OSTENDORP, 1989). One of the main factors is the mechanical damage of the reed front by waves and washes (BINZ-REIST, 1989; OSTENDORP, 1992, 1995). The abundance of drifting matter like drift wood, cultural debris, wash of submerged macrophytes is assumed to have been enhanced under the influence of man during the course of the century. As an example, the amount of wash that consisted of filamentous algae increased parallel to the lakes' nutrient load, since *Cladophora* and other algae species produced a higher standing crop under phosphorus enriched conditions. KLÖTZLI (1971), and RAGHI-ATRI & BORNKAMM (1980) postulated that, additionally, the improvement of nutrient supply leads to a decrease in sclerenchymatic tissue in *Phragmites* stems, bringing about a reduced power of resistance against mechanical load.

Different countermeasures were set about based upon different conceptions (OSTENDORP *et al.*, 1995). One idea was to improve the power of mechanical resistance of the reed stands to enable them to withstand the current mechanical threat with less losses of biomass than before. As long as the lake eutrophication and the nutrient load to the reedbeds were considered as a main factor, it was consequent to export nutrients from the reedbeds by winter reed-harvesting or by burning the dead culms of the previous year's crop (SCHRÖDER, 1979, 1987).

The hypothesis of SCHRÖDER (op. cit.) about the causes of the reed decline established the concept of the reed maintenance measures at Lake Constance: the die-back was suspected to have been initiated by the eutrophication of Lake Constance since the 1960s. The improved nutrient supply was thought to lead to an increased shoot density, and to a weakening of the stems. The broken stems were assumed to hinder the water exchange with the open littoral, and organic matter and nutrients to accumulate in the reedbed. During the decomposition of the organic matter oxygen was depleted in the overlaying water, and reduced substances (H_2S , CH_4) were released, which were thought to be toxic to *Phragmites* roots. The wash of filamentous algae exacerbated these detrimental effects. The idea of the reed maintenance measures was to export decomposable organic matter, and nutrients by mowing or burning the dead culms in winter and removing part of the litter and

the ash from the beds. Harvesting was done by different types of caterpillar vessels with an interchangeable mowing and chaffing device at the front. The chaffed straw and the litter were removed from the bed either by hand or by a machine, which sucked the material from the roller and blew it into a container. The work was usually carried out when the ground was deeply frozen (OSTENDORP *et al.*, 1995). The field experiments were monitored for several years to find out the ecosystem response of mown and burnt reed beds in comparison with the untreated references.

The purpose of this paper is to analyse and to evaluate the different effects of winter harvesting and burning on the power of the mechanical resistance of reed stands using the *PMR* model. This model postulates that the percentage of mechanically damaged shoots of a reed stand is a monotonically declining function of the mean stem diameter, the relative thickness of the stem wall, the modulus of elasticity, and the shoot density per square metre (OSTENDORP, 1995). Thereby it is possible to estimate the potential damage to mown or burnt reeds from stem stature and stand structure properties only.

AREA OF INVESTIGATION

The Untersee is the western part of Lake Constance (SW-Germany, Switzerland, 8°51'37"-9°08'23" E.L., 47°38'45"-47°44'17" north lat.), a shallow, eutrophic prealpine lake with high annual water level fluctuations (c. 1.9 m on average), broad shelves and extended reed belts. 99.7% of the eulittoral reeds are formed by monospecific stands of *Phragmites australis*, a perennial grass with stout culms, c. 6-13 mm in diameter at the stem base, and c. 2.5-4.5 m in height. The sublittoral zone is covered with submerged macrophytes, which are uprooted and washed ashore during storms, mainly in late summer and autumn (OSTENDORP, 1992).

In the first half of the century the reedbelts expanded to the mean low water bathymetric line, and in the 1950's a maximum area of 380 hectares was reached (German territory only). A dramatic die-back occurred between 1965 and 1980 when 37% of the lakeside reedbeds were lost (OSTENDORP, 1990).

METHODS

Several reed stands at the shore near the village of Moos at the western Untersee were selected to form pairs of treatment (table I). The stands are labelled with M (=mown), R (=reference), or B (=burnt) and consecutive numbers. Each stand consisted of 1 or two plots in the lakeside section of the reedbelt, or of 5 individual plots which formed a cross shore transect from the outermost (monospecific) *Phragmites* reeds to the landward reeds with an understorey of *Phalaris arundinacea*, *Carex* spp. and other wetland plants. Reed stands in the same row of table I are compared directly. Reed stands at the same place with different treatments in different years are marked with an asterisk. The other pairs represent stands of the same year at different places. Care was taken to select pairs of similar phenotypes, which were virtually unaffected by detrimental factors (e.g. mechanical load by waves and washes, grazing by waterfowl). The distance between such pairs was not greater than 30 m. There was no indication that the stands of the same pair derived from different clones. The weather during the three seasons of investigations was not monitored; hence, different weather conditions might have slightly influenced the stand structure in the series R1/B1/B2 and M4/M5. However, no strong bad weather periods (storm, hail, late frost, etc.) were observed.

TABLE I. – Treatment and sampling of test stands. M - mown, B - burnt, R - untreated reference; n - number of plots.

treatment and sampling				
winter mown: first season after the first treatment	winter mown: first season after the second treatment	untreated reference	winter burned: first season after the first treatment	winter burned: second season after the first treatment
M1 (n = 1)		R1 (n = 1)		
M2 (n = 5)		R2 (n = 5) (*)	B1 (n = 5) (*)	B2 (n = 5) (*)
M3 (n = 1)		R2 (n = 5)		
M4 (n = 2) (**)	M5 (n = 2) (**)		B3 (n = 1)	

(*), (**) - stands at the same location, but in different years.

no label - stands in the same year, but at different locations.

Sampling was performed in autumn or early winter. Each plot was sampled as follows:

- mean shoot density (n [# m⁻²]): means of 8 to 12 randomly selected test squares of 0.36 m² each. According to OSTENDORP & MÖLLER (1991) three shoot classes were differentiated: panicle bearing primary shoots (PSh), flowerless secondary shoots (SSh), and insect infested shoots (ISh). 12 to 24 representative stems were clipped at ground level and processed in the laboratory

- stem diameter at the half length of a stem (D [mm]): measured with a vernier calliper at each stem when it was air dried

- relative wall thickness of a stem (d_{rel} [% of 1/2 D]): mean of the thickness of the wall's cross section at four crosswise positions, measured under a stereomicroscope

- specific density of the stem wall material (ρ [mg cm⁻³]): estimated from the weight of the dry matter (70°C, 2 days), the mean diameter D, and the mean relative wall thickness d_{rel} of a double internode piece on the basis of a cylindric tube model

- bending stiffness (M_E [kN cm²]): a piece of two intact internodes were cut out from each stem, and tested, using the testing device described by BINZ-REIST (1989, p. 455-457); M_E was computed as

$$(1) \quad M_E = L^3/48 \cdot \Delta F/\Delta s$$

L - distance between the supporting points of the testing device,

F - force, applied to the double-internode piece just in the middle between the supporting points,

s - deflection of the double-internode piece at L/2 where the force F is applied with a calibrated spring balance

- modulus of elasticity (E [kN cm⁻²]): computed from the bending stiffness as

$$(2) \quad E = M_E/J = L^3/48 \cdot 1/J \cdot \Delta F/\Delta s$$

with

$$(3) \quad J = \pi/64 \cdot D^4 \cdot (1 - (1 - d_{rel}/100)^4)$$

J - moment of inertia

- breaking moment (M_S [N cm]): a double internode piece was adjusted on the testing device as described above, the force (applied to the node at L/2) was stepwise enhanced until the stem section failed (F_{br}); M_S was computed as

$$(4) \quad M_S = 1/4 \cdot L \cdot F_{br}$$

- breaking stress (S [kN cm^{-2}]): computed from the breaking moment as

$$(5) \quad S = 1/2 \cdot D/J \cdot L \cdot F_{br}$$

The mechanical stability of individual culms and *Phragmites* stands was assessed using the *pmr* and the *PMR* models, respectively (OSTENDORP, 1995): the power of mechanical resistance, *pmr*, is proportional to M_E (or M_S), and *PMR* is proportional to the sum of individual M_E values of all culms within a unit area:

$$(6) \quad \text{PMR} \propto \hat{M}_E = 1/A \sum M_{E,i}; i \text{ - culm in area } A$$

Pairs of treatments with more than three plots were compared using the paired t-test (n = number of plots), pairs with only one or two parallels were tested with the unpaired t-test in case of normal distribution of data and insignificantly different variances of the means, and the U-test otherwise (m = number of individual culms).

RESULTS

Effect on stem diameter and stand structure

Winter harvesting of reeds leads to extensive changes in stand structure (n [# m^{-2}], n [%] in table II *a*). The total shoot density increased significantly by 73% on average (*a*). This increase was to a greater part due to the enhanced abundance of SSh which increased threefold. The densities of PSh and ISh were not significantly affected. Thus, a winter mown reed stand consists of a greater percentage of SSh than the untreated reference, whereas the share of PSh is significantly lowered. Reed stands which were burnt down in winter, revealed similar changes in stand structure properties (*b*): total shoot density increased due to a threefold increase in SSh. The percentages of PSh and SSh changed conformably. There were no significant differences between the mown and the burnt stands (*c*), indicating that these two management procedures affect the reeds in the same way. If reed stands were treated two times in a row (*d*), the effect of a single treatment was accentuated with respect to the density and percentage of PSh and SSh; the total shoot density, however, decreases in these two plots. After the management was stopped, the stand structure parameters were reassigned the values they had before the treatment was begun, i.e. the total culm number decreased, mainly due to a decrease in SSh density. The percental composition changed significantly to the benefit of primary shoots (*e*). This was tested only for the pair "burnt"/"untreated". But it is assumed that these results will hold also for the winter harvesting treatment, since the changes in burnt stands were similar to those in mown reeds.

The *PMR* model postulates that the mechanical stability of a reed stand is positively connected with the shoot density. Hence, winter mown and burnt reeds should be better adjusted to mechanical threat than untreated reference stands, if all other relevant parameters remain constant.

The culms of mown reeds were significantly thinner, on average, than those of unmown stands (D [mm] in table II *a*). The background is, (i) that in all shoot classes "treated" culms exhibited smaller diameters than "untreated" ones, (ii) that the share of (thin) SSh increased in winter mown stands at the expense of (stout)

TABLE II. - Influence of treatment on shoot density (n [# m^{-2}], n [%]), stem properties (D , d_{rel} , ρ , E , S , M_E , M_S), and mechanical stand properties (\dot{M}_E , \dot{M}_S). Means and standard deviations (n - numbers of test plots, m - number of stems); s : test for statistical evaluation (n.s. - $\alpha > 0.05$, * - $\alpha \leq 0.05$, ** - $\alpha \leq 0.01$, *** - $\alpha \leq 0.001$). Standard deviations are given even if data are not normally distributed.

a	n	primary shoots			secondary shoots			insect infested shoots			total shoot population		
		M1+M2	R1+R2	M1+M2	M1+M2	R1+R2	M1+M2	M1+M2	R1+R2	M1+M2	R1+R2	M1+M2	R1+R2
n [# m^{-2}]	6	27.9 ± 5.3	n.s.	23.5 ± 4.2	22.7 ± 12.8	*	7.5 ± 5.5	5.3 ± 5.0	n.s.	1.4 ± 0.6	55.8 ± 19.9	*	32.3 ± 7.6
n [% of all shoots]	6	53.3 ± 13.6	*	73.8 ± 12.4	38.3 ± 12.0	*	21.9 ± 12.6	8.3 ± 7.4	n.s.	4.3 ± 1.8	100		100
D [mm]	6	6.30 ± 0.85	*	7.34 ± 1.48	4.21 ± 0.40	n.s.	4.62 ± 1.10	7.02 ± 0.53	n.s.	7.56 ± 1.72	5.53 ± 0.52	*	6.82 ± 1.57
d_{rel} [%]	6	14.4 ± 1.2	n.s.	13.9 ± 1.7	15.2 ± 1.3	n.s.	15.0 ± 2.0	15.8 ± 2.2	n.s.	15.0 ± 2.5	14.7 ± 1.2	n.s.	14.1 ± 1.9
ρ [mg cm^{-3}]	6	696 ± 40	n.s.	715 ± 69	537 ± 55	n.s.	545 ± 55	451 ± 44	***	542 ± 69	612 ± 42	n.s.	664 ± 86
E [10^6 N cm^{-2}]	6	1.89 ± 0.16	*	2.08 ± 0.26	1.21 ± 0.19	*	1.43 ± 0.12	1.00 ± 0.14	**	1.49 ± 0.29	1.54 ± 0.09	*	1.93 ± 0.30
S [10^3 N cm^{-2}]	6	45.0 ± 4.1	n.s.	45.1 ± 2.7	29.6 ± 3.1	n.s.	30.7 ± 3.4	25.1 ± 5.1	**	34.5 ± 5.1	37.0 ± 1.9	*	41.5 ± 3.6
M_E [10^3 N cm^2]	6	7.9 ± 3.5	*	16.2 ± 8.5	1.1 ± 0.3	n.s.	2.1 ± 0.5	5.3 ± 2.5	n.s.	13.6 ± 8.5	4.9 ± 1.8	*	13.7 ± 8.0
M_S [N cm]	6	0.40 ± 0.22	*	0.84 ± 0.36	0.12 ± 0.03	n.s.	0.17 ± 0.10	0.43 ± 0.07	n.s.	0.74 ± 0.62	0.35 ± 0.11	*	0.72 ± 0.34
\dot{M}_E [10^3 N cm^2 m^{-2}]	6	217 ± 92	*	400 ± 233	27 ± 23	n.s.	19 ± 29	35 ± 35	n.s.	21 ± 18	278 ± 126	n.s.	440 ± 255
\dot{M}_S [N cm m^{-2}]	6	14.8 ± 6.0	n.s.	20.7 ± 10.2	2.8 ± 1.9	*	1.5 ± 2.0	2.2 ± 2.1	n.s.	1.1 ± 0.8	19.8 ± 8.5	n.s.	23.3 ± 11.8

TABLE II. - Continued

b	n	B1		R2		B1		R2		B1		R2			
		M3	(m=6...7)	B3	(m=5)	M3	(m=7)	B3	(m=5...6)	M3	(m=2)	B3	(m=1)	M3	(m=15...16)
n [# m ⁻²]	5	20.2 ± 10.0	n.s.	22.5 ± 3.8	17.4 ± 7.9	**	5.7 ± 3.8	10.1 ± 4.2	**	13.0 ± 0.6	47.6 ± 15.6	*	29.4 ± 2.9		
n [% of all shoots]	5	41.1 ± 11.4	*	76.4 ± 11.9	35.6 ± 4.9	*	19.4 ± 12.3	23.3 ± 12.2	*	4.3 ± 2.0	100	-	100		
D [mm]	5	6.50 ± 0.85	n.s.	7.16 ± 1.58	4.23 ± 0.56	n.s.	4.31 ± 0.90	6.53 ± 1.28	n.s.	7.13 ± 1.53	5.75 ± 0.81	n.s.	6.67 ± 1.71		
d _{rel} [%]	5	15.9 ± 1.8	***	14.0 ± 1.8	16.6 ± 1.8	**	15.4 ± 2.0	17.2 ± 2.1	n.s.	15.2 ± 2.8	16.5 ± 1.7	**	14.3 ± 2.1		
ρ [mg cm ⁻³]	5	635 ± 17	***	740 ± 31	497 ± 32	*	562 ± 41	481 ± 18	**	568 ± 29	533 ± 24	**	690 ± 65		
E [10 ⁶ N cm ⁻²]	5	1.69 ± 0.09	**	2.15 ± 0.03	1.14 ± 0.16	*	1.47 ± 0.06	1.07 ± 0.03	**	1.57 ± 0.25	1.34 ± 0.11	**	2.01 ± 0.25		
S [10 ³ N cm ⁻²]	5	44.0 ± 45.8	n.s.	45.8 ± 2.2	28.7 ± 5.6	n.s.	31.0 ± 3.7	31.8 ± 3.7	n.s.	36.2 ± 3.4	35.3 ± 4.1	*	42.6 ± 2.9		
M _E [10 ³ N cm ⁻²]	5	10.5 ± 5.3	n.s.	15.6 ± 9.4	1.2 ± 0.5	n.s.	1.6 ± 0.8	7.5 ± 5.4	n.s.	11.7 ± 8.0	6.5 ± 3.2	*	13.6 ± 8.9		
M _S [N cm]	5	0.66 ± 0.20	n.s.	0.80 ± 0.38	0.13 ± 0.03	n.s.	0.14 ± 0.06	0.53 ± 0.26	n.s.	0.66 ± 0.35	0.45 ± 0.15	n.s.	0.70 ± 0.37		
M _E [10 ³ N cm ² m ⁻²]	5	173 ± 27	n.s.	332 ± 249	19 ± 7	**	7 ± 5	86 ± 65	n.s.	16 ± 14	277 ± 83	n.s.	395 ± 257		
M _S [N cm m ⁻²]	5	11.7 ± 2.3	n.s.	18.8 ± 10.2	2.1 ± 0.6	***	0.7 ± 0.5	5.9 ± 3.5	*	0.9 ± 0.6	19.8 ± 2.4	n.s.	20.3 ± 10.5		

c	n	M3		B3		M3		B3		M3		B3	
		(m=6...7)	(m=5)	M3	(m=7)	B3	(m=5...6)	M3	(m=2)	B3	(m=1)	M3	(m=15...16)
n [# m ⁻²]	1	19.9	-	18.5	66.5	-	72.2	6.0	-	8.8	92.6	-	99.5
n [% of all shoots]	1	21.5	-	18.6	72.0	-	72.2	6.5	-	8.8	100	-	100
D [mm]	1	6.67 ± 1.62	n.s.	6.23 ± 2.08	4.05 ± 0.78	n.s.	3.43 ± 0.35	7.33	-	6.01	4.83 ± 1.60	n.s.	4.18 ± 1.54
d _{rel} [%]	1	14.7 ± 1.0	n.s.	14.6 ± 1.1	15.6 ± 1.1	n.s.	14.1 ± 1.0	15.9	-	16.5	15.5 ± 1.1	*	14.4 ± 1.2
ρ [mg cm ⁻³]	1	698 ± 54	n.s.	661 ± 34	515 ± 69	n.s.	522 ± 31	388	-	453	546 ± 107	n.s.	542 ± 67
E [10 ⁶ N cm ⁻²]	1	1.87 ± 0.09	n.s.	1.74 ± 0.17	1.21 ± 0.78	n.s.	1.28 ± 0.14	0.77	-	1.16	1.33 ± 0.73	n.s.	1.35 ± 0.23
S [10 ³ N cm ⁻²]	1	52.1 ± 6.4	n.s.	47.6 ± 3.1	29.2 ± 10.6	n.s.	31.2 ± 8.6	22.9	-	32.4	33.7 ± 13.6	n.s.	34.4 ± 9.8
M _E [10 ³ N cm ⁻²]	1	9.3 ± 8.7	n.s.	8.7 ± 11.1	0.9 ± 0.8	n.s.	0.6 ± 0.2	6.5	-	4.1	3.1 ± 5.4	n.s.	2.4 ± 5.7
M _S [N cm]	1	0.67 ± 0.43	n.s.	0.61 ± 0.57	0.11 ± 0.10	n.s.	0.08 ± 0.04	0.51	-	0.37	0.26 ± 0.32	n.s.	0.20 ± 0.32
M _E [10 ³ N cm ² m ⁻²]	1	185	-	162	63	-	41	39	-	36	287	-	239
M _S [N cm m ⁻²]	1	13.3	-	11.3	7.4	-	5.5	3.0	-	3.3	23.9	-	20.1

TABLE II. - Continued

<i>d</i>	<i>n</i>	M4 (<i>m</i> = 12)	M5 (<i>m</i> = 10)	M4 (<i>m</i> = 8)	M5 (<i>m</i> = 12)	M4 (<i>m</i> = 3)	M5 (<i>m</i> = 2)	M4 (<i>m</i> = 23)	M5 (<i>m</i> = 24)
<i>n</i> [# m ⁻²]	2	23.1	14.3	14.5	17.9	5.0	1.8	42.5	34.0
<i>n</i> [% of all shoots]	2	54.4	42.1	34.1	52.6	11.8	5.3	100	100
<i>D</i> [mm]	2	6.73 ± 1.73	n.s. 7.31 ± 1.23	4.09 ± 0.69 *	5.00 ± 1.00	7.25 ± 1.62	n.s. 7.06 ± 0.03	5.89 ± 1.93	6.08 ± 1.57
<i>d_{rel}</i> [%]	2	13.7 ± 0.4	* 14.6 ± 1.0	14.9 ± 0.9	n.s. 15.8 ± 1.2	14.1 ± 1.7	n.s. 15.1 ± 0.1	14.1 ± 1.0	** 15.2 ± 1.2
<i>ρ</i> [mg cm ⁻³]	2	727 ± 60	** 632 ± 74	548 ± 115	* 458 ± 45	464 ± 39	n.s. 481 ± 2	635 ± 131	** 532 ± 103
<i>E</i> [10 ⁶ N cm ⁻²]	2	1.93 ± 0.26	* 1.61 ± 0.33	1.06 ± 0.45	n.s. 0.89 ± 0.20	1.02 ± 0.22	n.s. 1.12 ± 0.12	1.52 ± 0.55	* 1.20 ± 0.44
<i>S</i> [10 ³ N cm ⁻²]	2	45.5 ± 5.1	n.s. 41.7 ± 6.4	28.7 ± 12.0	n.s. 27.7 ± 5.9	26.1 ± 3.2	n.s. 30.0 ± 2.7	37.5 ± 11.8	n.s. 33.7 ± 9.1
<i>M_E</i> [10 ³ N cm ²]	2	9.4 ± 9.5	* 12.1 ± 8.4	0.9 ± 0.5	n.s. 1.7 ± 1.5	7.4 ± 4.9	n.s. 7.7 ± 1.6	6.2 ± 8.1	n.s. 6.4 ± 7.5
<i>M_S</i> [N cm]	2	0.61 ± 0.43	n.s. 0.79 ± 0.38	0.11 ± 0.06	n.s. 0.22 ± 0.16	0.50 ± 0.23	n.s. 0.57 ± 0.10	0.43 ± 0.40	n.s. 0.48 ± 0.39
<i>M_E</i> [10 ³ N cm ² m ⁻²]	2	216	173	13	30	37	14	266	217
<i>M_S</i> [N cm m ⁻²]	2	14.1	11.3	1.7	3.9	2.5	1.0	18.3	16.2

<i>e</i>	<i>n</i>	B1	B2	B1	B2	B1	B2	B1	B2
<i>n</i> [# m ⁻²]	5	20.1 ± 10.0	* 38.4 ± 8.5	17.4 ± 7.9	n.s. 10.4 ± 3.2	10.1 ± 4.2	** 0.9 ± 0.8	47.6 ± 15.6	n.s. 49.7 ± 9.8
<i>n</i> [% of all shoots]	5	41.1 ± 11.4	** 77.0 ± 4.7	35.6 ± 4.9	** 20.9 ± 4.9	23.3 ± 12.2	* 2.0 ± 2.1	100	100
<i>D</i> [mm]	5	6.50 ± 0.84	* 7.41 ± 8.0	4.24 ± 0.58	* 5.69 ± 1.23	6.53 ± 1.28	n.s. 6.78 ± 0.71	5.75 ± 0.81	** 7.01 ± 0.88
<i>d_{rel}</i> [%]	5	15.9 ± 1.8	n.s. 15.1 ± 1.9	16.6 ± 1.8	** 15.2 ± 2.2	17.2 ± 2.1	n.s. 15.7 ± 3.2	16.5 ± 1.7	** 15.1 ± 2.0
<i>ρ</i> [mg cm ⁻³]	5	635 ± 17	** 695 ± 19	497 ± 32	n.s. 552 ± 60	481 ± 17	n.s. 517 ± 50	533 ± 24	*** 661 ± 21
<i>E</i> [10 ⁶ N cm ⁻²]	5	1.69 ± 0.08	*** 2.19 ± 0.07	1.14 ± 0.17	n.s. 1.41 ± 0.21	1.07 ± 0.03	n.s. 1.43 ± 0.23	1.34 ± 0.11	*** 2.01 ± 0.09
<i>M_E</i> [10 ³ N cm ²]	5	10.5 ± 5.3	* 16.4 ± 5.0	1.2 ± 0.5	* 4.0 ± 2.4	7.5 ± 5.4	n.s. 7.8 ± 2.9	6.5 ± 3.2	** 13.7 ± 4.3
<i>M_E</i> [10 ³ N cm ² m ⁻²]	5	173 ± 27	* 651 ± 264	19 ± 7	n.s. 47 ± 40	86 ± 65	* 6 ± 5	277 ± 83	* 624 ± 263

PSh. Similarly, the mean stem diameter was lowered in each shoot class in the fire treatment. The mean differences were, however, not always significant (*b*). The mean stem diameters in each shoot class of the mown stand did not differ significantly from those of the burnt stand (*c*). This was also the case for the treatments M4 and M5 (*d*). All shoot classes had thicker shoots in the vegetation period after the treatment was stopped (*e*).

The stem diameter D determines to a great part the bending stiffness and the breaking moment, as M_E and M_S are proportional to D^4 . For all shoot classes D is higher in the untreated reference than in both treatments, which are therefore more susceptible to mechanical load, if the other factors are constant.

Effect on stem wall properties

Not only the geometry of the stem was affected by winter harvesting and burning, but also the cross-sectional dimensions of the stem, and the mechanical properties of the stem wall material (table II).

The mean relative wall thickness (d_{rel}), was always higher in SSh, and in ISh than in PSh, with the exception of treatment B3 in table II *d*. Mowing and burning led to a small and insignificant increase in mean d_{rel} of all shoot classes, except in SSh in B1/R2 (*a, b*). The differences between the two kinds of treatment were not significant for any shoot class (*c*). After a second subsequent harvesting period, d_{rel} increased significantly once more (*d*). Mean d_{rel} values decreased, after the treatment was stopped, but remained still higher than in the untreated reference (*e*). However, many of these changes are not significant on the $\alpha = 5\%$ level. The mean d_{rel} value of the total culm population is the result of changes within each shoot class and their relative proportions. Hence, the grand mean of the relative wall thickness increased under the treatment (*a, b*), and decreased significantly when the treatment was stopped (*e*).

The relative wall thickness is of interest in this context, because the bending stiffness M_E and the breaking moment M_S change parallel to d_{rel} , if the other parameters remain constant (see (2)). Under this condition the treated reeds should have an advantage in mechanical resistance to waves and washes.

The mean specific density of the stem wall (ρ) of the SSh was found to be consistently lower than that of the PSh, and the values of the ISh underbid those of the SSh (table II). Mowing and burning resulted in a ρ reduction in all shoot classes (*a, b*) especially after two subsequent harvesting treatments (*d*). No significant difference could be observed between the mown and the burnt stands (*c*). After a treated stand was left to itself, the mean specific density re-developed to higher values, which reached those of the untreated references (*e*). The ρ values of the total shoot population followed this pattern for the same reasons as mentioned above.

The specific density of the stem wall tissue can be taken as a measure of the share of thick-walled sclerenchymatic cells in a matrix of thin-walled parenchymatic tissue and aerenchymatic channels. For that reason ρ is positively correlated with the modulus of elasticity, E , and the breaking stress S . Hence, it is concluded that the mechanical properties M_E and M_S of the stem are proportional to the specific density, if all other parameters remain constant. As to ρ , untreated reeds have an advantage over mown and burnt stands.

The SSh were consistently weaker than the PSh with respect to the modulus of elasticity (E), and the breaking stress (S). For the ISh and the SSh there is no such clearcut difference (table II). Winter harvesting and burning reduced E significantly in all shoot classes. The decrease in S was less pronounced, and not significant in most cases (a, b). A twofold treatment resulted in a further reduction of E and S in PSh and SSh (d). No significant differences occur between mown and burnt stands (c). After having been left untreated one time, a burnt stand reveals higher mean E values in all shoot classes than before (e). They are as high as in R1 and R2, which have never been treated before. With regard to the total culm population the E and S values follow the same pattern, being significant in most cases (not, of course, between M3 and B3).

The modulus of elasticity and the breaking stress are parameters, which directly measure the mechanical properties of a reed culm, i.e. the force that induces a given deflection from the equilibrium shape of a stem section, and the force that is needed to break a stem at a given design of the testing device (BINZ-REIST, 1989). Treated reeds show significantly lower E and S values than the untreated references. Thus, if the other parameters, like D and d_{rel} , are constant, the mechanical stability of a treated reed culm is decreased parallel to E , and S , respectively.

Effect on the power of mechanical resistance of individual stems

The bending stiffness of a reed culm, M_E , at a given height above the ground, as near as possible to the most probable point of mechanical threat, has been proved to be a good indicator of the mechanical resistance pmr of a single *Phragmites* culm under field conditions (OSTENDORP, 1995). The same, but not so precise, holds for the bending moment M_S , because M_E and M_S depend on the same parameter, the diameter D .

Mean M_E and M_S values were much lower in SSh and ISh than in PSh, because they were thinner (D) and weaker (E, S). The enhanced relative wall thickness of these two shoot classes did not compensate for the reduced stem diameter (table II).

Winter harvesting and burning resulted in a significant decrease in mean M_E for PSh as well as if the total shoot population is regarded (a, b). The M_E values of SSh and ISh were affected in the same way. The breaking moment M_S followed the same pattern. Two mowing treatments yielded no marked differences in M_E and M_S on the basis of the whole culm population. This was due to a shift in shoot class percentages (d). Within each shoot class the M_E and M_S values increased insignificantly. No significant difference could be found between winter harvesting and fire management (c). Burnt stands developed towards untreated stands when they were not treated again, exhibiting greater M_E values in all shoot classes, and in the total shoot population (e). M_S was not recorded for this pair of treatment.

The maximum differences between the cumulative M_E (and M_S) frequency distributions of two stem populations have been used to test the validity and the accuracy of the pmr -model. The accuracy is equal to the maximum distance ∂_{max} [%] between the two frequency curves. The M_E value for which ∂ yields ∂_{max} gives an indication of the strength of the mechanical impact (" M_E -equivalent" strength) (OSTENDORP, 1995). Comparing for instance the M_E frequency distributions of an untreated stand and of a mown stand, it is possible to estimate the percentages of culms which will fail in each stand under a distinctive M_E -equivalent mechanical

load, figure 1 gives an example. The M_E data of the outermost three (stands R2, B1, and B2) or four (stand M2) lakeside plots were pooled to construct the curves in figures 1 and 2. This was possible since the lakeside plots were homogenous, whereas the one or two landward plots showed greater differences in stem stature, and pedological and hydrological conditions.

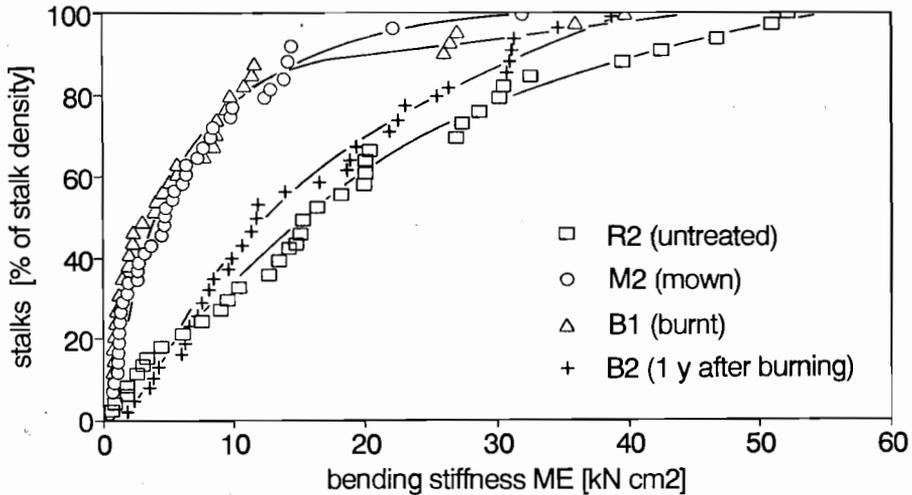


Fig. 1. - Cumulative distribution of the culm number (100% - mean shoot density, s. table III) over the bending stiffness M_E ; the cumulative culm number is weighted for the proportions of the three shoot classes in each plot.

It can be seen from figure 1 that the untreated reference (R2) had a higher percentage of stronger culms than the mown or the burnt stand (M2, B1) for any given M_E value. For the comparison M2/R2 ∂ is at maximum ($\partial_{\max} = 51\%$) at $M_{E,\text{crit}} = 12 \text{ kN cm}^2$, and for the pair B1/B2 ∂_{\max} yields 45% at $M_{E,\text{crit}} = 11 \text{ kN cm}^2$. This means that for an M_E -equivalent mechanical impact of c. 11 kN cm^2 the untreated stand R2 will loose 36% of its stems (i.e. those with M_E values lower than 11 kN cm^2), but in M2 and B1 more than 80% of the culms will fail. For any given strength of the mechanical impact the untreated stand R2 will be damaged to a lesser degree than the mown and the burnt stands. Discussing the results of table II it was stated that a burnt stand, that has been left untreated for one period (B2) re-develops towards the untreated reference. This is also demonstrated by its M_E distribution in figure 1: ∂_{\max} between the frequency distributions of B2 and R2 is less than c. 14% for any given $M_{E,\text{crit}}$ value, i.e. for $M_E > 8 \text{ kN cm}^2$ B2 will lose some more culms than R2, and for $M_E < 8 \text{ kN cm}^2$ the reverse will hold.

In figure 2 the cumulative biomass distribution of the stems is plotted against their bending stiffness. Evidently, the untreated reference (R2) had smaller percentages of biomass of culms whose bending stiffness fell below a given M_E value than the "mown" and the "burnt" treatment (M2, B1). ∂_{\max} is 55% (comparison M2/R2), and 40% (B1/R2) at $M_{E,\text{crit}} = 12 \text{ kN cm}^2$. It is concluded that, if a M_E -equivalent mechanical load of c. 12 kN cm^2 acts on these stands, R2 will lose c. 20% of its biomass, whereas in M2 and B1 the percentage of damaged

biomass is substantially higher (75%, and 62%, respectively). The distribution curves of B2 and R2 are close to one another, and δ_{\max} is not greater than 22% at 40 kN cm², and less than 12% at low critical bending moments. The risks of losing a definite proportion of biomass by mechanical damage is therefore similar in both stands.

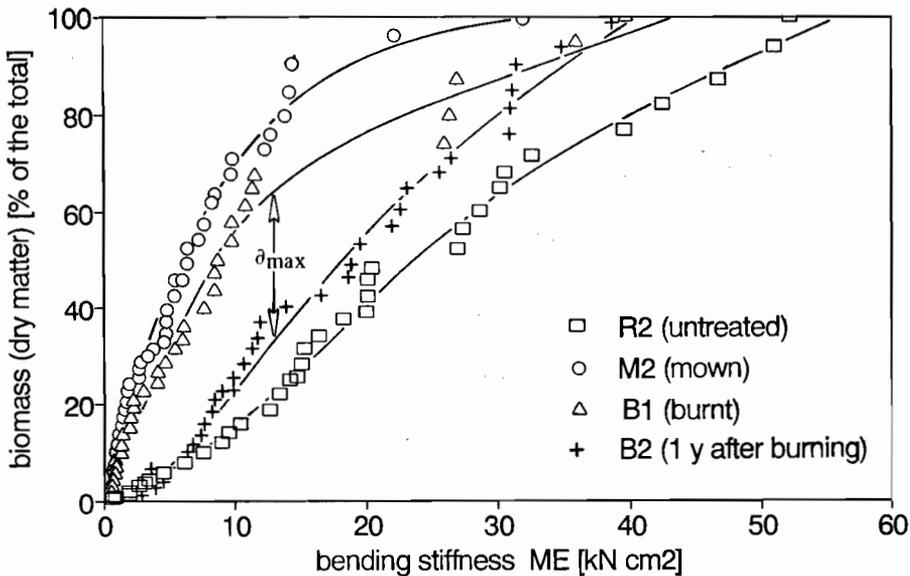


Fig. 2. - Cumulative distribution of the culm biomass (100% - mean standing crop) over the bending stiffness M_E ; the cumulative culm biomass is weighted for the proportions of the three shoot classes in each plot.

Effect on the power of mechanical resistance of *Phragmites* stands

It has been demonstrated that the sum of M_E values of all culms within an unit area (e.g. 1 m²) is a fairly good approach to the power of mechanical resistance of an intact *Phragmites* stand, as this value is negatively correlated to the percentage of damaged culms, and damaged biomass, respectively (PMR model, OSTENDORP, 1995).

The data in table II show that the sum of bending moments \hat{M}_E is by far greater in the untreated reference than in the "mown" and in the "burnt" treatments. This implies that treated reeds will suffer greater damage than untreated stands, when they are affected by mechanical impacts of the same strength.

To analyse and to explain the \hat{M}_E differences between treatments, the data were pooled as described in the previous section. The results are compiled in table III. The \hat{M}_E of a stand can be computed from the shoot density and the mean characteristics, E' and J' , of an average culm:

$$(7) \quad \hat{M}_E = n \cdot E' \cdot J'$$

TABLE III. - Means of shoot density, modulus of elasticity, moment of inertia, bending stiffness and \hat{M}_E for the lakeward plots of the test stands R2, M2, B1, and B2 (total culm population); n - number of plots, m - number of culms; means are weighted for the proportions of the three shoot classes in each plot.

	R 2 (n=3, m=36)	M 2 (n=4, m=48)	B 1 (n=3, m=36)	B 2 (n=3, m=36)
n [# m ⁻²]	28.4	59.0	37.8	52.5
E [10 ⁶ N cm ⁻²]	2.15	1.57	1.30	1.98
J [10 ⁻³ cm ⁴]	9.09	3.17	5.64	7.48
M _E [kN cm ²]	19.83	5.12	8.07	15.86
\hat{M}_E [kN cm ² m ⁻²]	557	294	277	775

The \hat{M}_E difference between two treatments, 1 and 2, $\Delta\hat{M}_E$, can be written as

$$(8) \quad \Delta\hat{M}_E = \hat{M}_{E,1} - \hat{M}_{E,2}$$

$$(9) \quad \hat{M}_{E,1} = (n_1 + \Delta n) (E'_1 + \Delta E) (J'_1 + \Delta J)$$

The significance of, for instance, Δn can be estimated by comparing $\Delta\hat{M}_E$ with $\Delta\hat{M}_E^*$. For $\Delta\hat{M}_E^*$ Δn is set to zero, i.e. a change in n is ignored. E and J are treated correspondingly. The results are given in table IV.

TABLE IV. - Effect of shoot density (n), modulus of elasticity (E) and moment of inertia (J) on the power of mechanical resistance ($\Delta\hat{M}_E$ - difference between two treatments 1 and 2), s. text for explanations.

index #) treatment/stand	1	2	1	2	1	2	1	2
	M 2	R 2	B 1	R 2	B 1	M 2	B 2	R 2
$\Delta\hat{M}_E$ [kN cm ² m ⁻²]		-263		-280		-17		+218
$\Delta\hat{M}_E^*$ ($\Delta n=0$) [kN cm ² m ⁻²]		-415		-348		+139		-137
$\Delta\hat{M}_E^*$ ($\Delta E=0$) [kN cm ² m ⁻²]		-154		-98		+41		+288
$\Delta\hat{M}_E^*$ ($\Delta J=0$) [kN cm ² m ⁻²]		+286		-110		-138		+386

#) association between treatment/stand and index in the formula $\Delta\hat{M}_E = \hat{M}_{E,1} - \hat{M}_{E,2}$.

For the comparison M2/R2, $\Delta\hat{M}_E$ is negative ($\Delta\hat{M}_E = -263$ kN cm² m⁻²). The difference would be even greater, if the shoot density would remain unchanged ($\Delta\hat{M}_E^* = -415$ kN cm² m⁻²). This means that the change in n has a conservative effect in the sense that it tends to minimize $\Delta\hat{M}_E$. The reverse is the case for the modulus of elasticity. The reduction of the mean stem diameter, and consequently the reduction of the moment of inertia J, is the most important factor which contributes to the reduction of \hat{M}_E when a reed stand is mown. If it would have remained constant ($\Delta J=0$), the \hat{M}_E value of the mown stand would be even greater than that of the reference.

In the case of R2 vs. B1, ΔE and ΔJ contribute the bulk to $\Delta\hat{M}_E = -280$ kN cm² m⁻², whereas the increase in n tends to keep the difference low. The reduction in mechanical stability is therefore mainly due to thinner culms (J) and weaker stem wall tissue (E). The \hat{M}_E difference between the mown (M2)

and burnt stands (B1) is small, and changes of all parameters are of importance. The stand B2, which has been left unaffected after one burning treatment, has a positive $\Delta\hat{M}_E$ value in relation to R2. This increase can be explained mainly by the increase in shoot density, whereas the changes in E and D (or J, respectively) tend to reduce the \hat{M}_E difference. It can be stated that, generally, changes in stem diameter and in shoot density exert the greatest influence upon the \hat{M}_E differences.

DISCUSSION

Stands of the common reed, *Phragmites australis*, consist of three shoot classes: the panicle bearing primary (=terminal) shoots (PSh), the flowerless secondary (=lateral) shoots (SSh) and the insect infested shoots (ISh); the latter are also lacking inflorescences (OSTENDORP & MÖLLER, 1991). This composition occurs in unaffected stands as well as in mechanically damaged, winter harvested or winter burnt stands.

The proportions of these shoot classes, however, vary depending on the treatment. In unaffected stands the percentage of SSh is low (c. 20%, see table II: R1, R2, and B2), and the proportion of primary shoots (PSh) exceeds 70%. Normally, the percentage of ISh is low in lakeside reeds (<5%). In this study treated stands are more affected by insect attack than untreated ones; the percentage of ISh is more than doubled, on average. After treatment (mowing and burning) the percentage of SSh increases by c. 15% on average, and the corresponding values of PSh decline by 20 to 35% (table II: M1, M2, B1). SSh derive from lateral meristems in the nodes of upright rhizomes which shoot, when the apical dominance of the PSh is abolished due to different kinds of injury to the apical meristem (mechanical injury, fire, insect attack) (HASLAM, 1969; PHILLIPS, 1975). Repeated treatments in subsequent winters accentuate the shift from PSh to SSh (table II: M4/M5). When the treatment is stopped, the new developing (apical) buds regain their apical control over subapical meristems, and the percentage of SSh drops to former values (table II: B2/B1).

The ISh consist mainly of non-flowering shoots, whose apex is damaged by larvae of the fly *Lipara* sp. (Chloropidae, Diptera-Brachycera) or of the moth *Archanara geminipunctata* (Haworth) (Noctuidae, Lepidoptera). The abundance of ISh depends on many factors, including the behaviour and the ecological requirements of these phytophagous insect species, both adults and larvae (OSTENDORP, 1993).

Primary and secondary shoots differ from each other in most properties (table II): the SSh are thinner (D) than PSh, they exhibit a lower density of the stem wall tissue (ρ), and they are weaker in respect to E and S. The increased stem wall thickness (d_{rel}) cannot compensate for this, what leads to a consistently lower bending stiffness M_E and breaking moment M_S . This result emphasizes the hypothesis that the physiological integration levels of these two shoot classes are different, and that generally the SSh form the less vital shoot class. It is concluded that, according to the M_E and M_S values, the power of mechanical resistance of SSh will be less than that of PSh under field conditions. The analysis of mechanically damaged reed stands from the Lake Constance-Untersee shore confirms this conclusion (OSTENDORP, 1995).

Winter harvesting and burning influence the culm properties in PSh and SSh negatively (table II: M1+M2/R1+R2, and B1/B2): the culms become thinner (D), they are weaker (E), and the mean density of the stem wall tissue (ρ) is lower, but the stem wall thickness (d_{rel}) increases. Hence, the M_E (and M_S) values are lower in both shoot classes. The differences of means between treated and untreated stands are, however, not always significant. This is due to the great within-stand variability which was compensated for, to some extent, by combining the sampling plots to cross-shore transects. The changes in D, d_{rel} , ρ , E, and M_E are reversible for PSh as well as for SSh when the treatment is stopped (cf. B1/B2).

The grand means which refer to the total culm population depend on the mean properties in each shoot class, and the percentage of each shoot class. Figure 3 summarizes the percental changes of the means of n , D, E, M_E and \hat{M}_E for a sequence beginning with an untreated reference (=100%; R1+R2) to a treated stand, that has been left to itself for one season (B2). Evidently, mowing and burning is attended by an increase in total shoot density, and by a reduction in mean D, E, M_E , and \hat{M}_E . The \hat{M}_E value strongly depends on D and n . However, the increase in n cannot compensate for the decrease of D. After the treatment stopped, the shoot density remains high which results in a higher \hat{M}_E value than in the untreated reference.

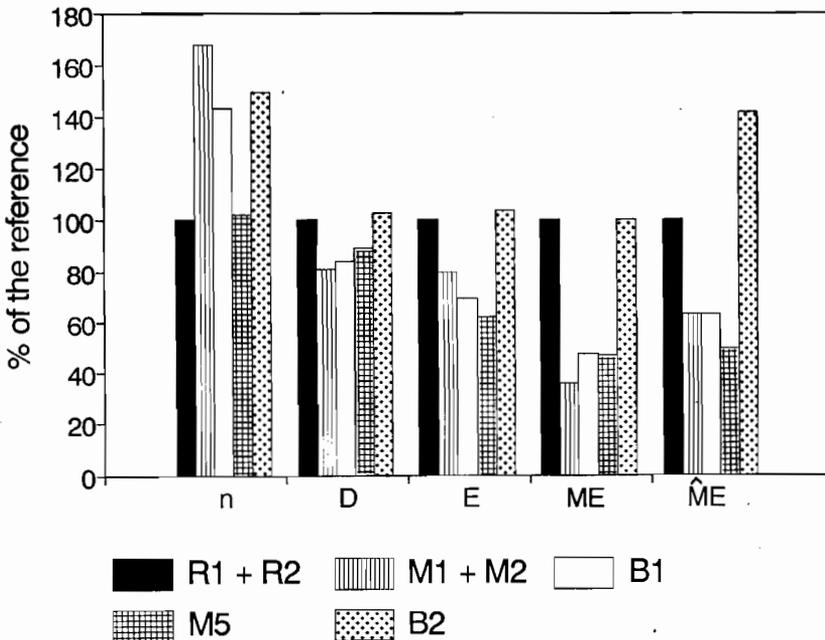


FIG. 3. - Percental changes of shoot density (n), stem diameter (D), modulus of elasticity (E), bending stiffness (M_E), and \hat{M}_E . A group of columns represents a sequence of treatments: untreated (R1+R2) → treated for the first time (M1+M2, and B1) → treated for the second time (M5) → left unaffected for one season after treatment (B2).

Comparing the M_E frequency distributions, for instance, of an untreated stand and of a winter harvested stand, it is possible to estimate the proportions of culms which will fail in each stand under a given M_E -equivalent mechanical load. The model implies that mown and burnt stands will lose substantially more culms and biomass than untreated reeds (figs. 1, 2). This is especially true in cases of relatively low energy input. The stronger the impact, the smaller is the difference, and treated and untreated stands will at last lose similar amounts of culms or biomass.

The *PMR* model refers to the current season's culm generation alone. Under field conditions, however, many culms of the previous year's crop are still standing upright, and contribute to the total \hat{M}_E of the reed stand, though their individual M_E values may be reduced due to weathering and fungal decay of the stem wall tissue (BOSMAN, 1985). Obviously, mown and burnt stands lack the previous year's culm generation. This reduces their power of mechanical resistance in addition to the low \hat{M}_E of the current season's culm population.

In principle, differences in susceptibility to mechanical damage between treated and untreated reeds could be either stated by field experiments (controlled wave generation with big vessels, see HUBER & WEISS, 1986), or by statistically comparing a number of such pairs, each at similar shore sections, and under comparable circumstances. At Lake Constance it turned out, however, that both approaches were impracticable. Littoral shoals did not allow navigation of big vessels. Place and time of storm events with wave propagation perpendicular to the shore line could not be forecasted, so that the installation of wave height recording devices seemed to be ineffective. Additionally, the reed front is irregularly shaped with many bights and indentations, which caused a high longshore variation in wave force and drifting matter abundance. Hence, no one pair of treated/untreated reeds could be identified that was damaged by the same external forces. It was therefore reasonable to use the *PMR* model to compare reed stands as to their potential (!) resistance against mechanical impact in the field, irrespectively whether these impacts will take place or not.

Many field observations, which cannot be quantified for the above mentioned reasons, support this model. Figure 4 gives an example. Here, a reed belt of c. 1.6 hectare with a shore length of 320 m was harvested in winter. Only a few spots at the reed front remained untreated. In September when the high summer water level had dropped down, it became clear that the mown reed section was by far more seriously damaged than the untreated spots.

Initially the purpose of winter harvesting and fire treatment was to improve the mechanical stability of the culms. It must be stated now, that, contrary to this intention, mowing and burning lead to a decrease in mechanical stability and to an enhanced endangering of the reeds. In the 1980s a total of 12.4 hectares of lakeside reeds (i.e. 2.9 km shorelength) were winter harvested and burnt at Lake Constance-Untersee. From this area 2.4 hectares died off. Roughly one third of it was due to mechanical damage by waves and washes.

Other aspects of management impacts upon the functioning of reeds in landscape ecology have been discussed by OSTENDORP (1993). Based upon experiments from Lake Constance and from other European lakes it was argued that negative influences exceed positive ones, at least for benthic invertebrates, and breeding birds.



FIG. 4. – Reed belt near the mouth of the Radolfzeller Aach, Lake Constance-Untersee: left-hand side - mown section, right-hand side - untreated section. The culms of the mown stand are bent down to the ground, and many leaves are stripped off; the damaged zone is c. 5 m wide. The culms of the untreated section stand upright and are nearly unaffected.

Hence, the benefit of this kind of reed management is dubious, and therefore it cannot be recommended as a reed maintenance measure. Alternate management, maintenance and protection practices have been discussed by OSTENDORP *et al.* (1995).

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