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Hydrology of Drained and Undrained Black Spruce Peatlands: Groundwater Table Profiles and Fluctuations

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ABSTRACT

Water-table profiles for the snow-free months of 1987, 1988 and 1989 were examined in forested and clearcut peatlands subjected to various drainage-ditch spacings. Four vegetation types from the northern Ontario Forest Ecosystem Classification were represented. Depth to water from the peat surface decreased as distance from the ditch increased and as ditch spacing increased. Differences in depth to the water table among vegetation types with similar ditch spacings were attributed to differences in peat depth. The optimum ditch spacing for each vegetation type was selected so that the rooting zone of the main crop-tree species is not under saturated or near-saturated moisture conditions. Recommended spacings ranged from 35 to 40 m, with wider spacings for vegetation types with thin peat layers. These spacings were also applicable to the harvested areas.

RÉSUMÉ

Pour les mois sans neige de 1987, de 1988 et de 1989, le profil de la nappe phréatique a été examiné dans les tourbières boisées et déboisées par coupe rase où divers espacements de fossés de drainage ont été expérimentés. Quatre types de végétation figurant dans la classification des écosystèmes forestiers du nord de l'Ontario étaient représentés. La distance entre la surface de la tourbe et la nappe phréatique variait de façon inversement proportionnelle à la distance et à l'espacement des fossés. Pour des espacements semblables, les différences de distance entre la tourbe et la nappe phréatique ont été attribuées aux différences d'épaisseur de la tourbe. Pour chaque type de végétation, l'espacement optimal des fossés a été choisi de façon que l'horizon racinaire de la principale espèce du peuplement final ne soit pas sous-saturé ou presque saturé d'eau. Les espacements recommandés variaient de 35 à 40 m et devaient être plus grands pour les types de végétation où la couche de tourbe était mince. Ces recommandations étaient les mêmes pour les zones exploitées.

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INTRODUCTION

In Ontario, about 46% of the 17.4 million ha of productive black spruce (*Picea mariana* [Mill.] B.S.P.) forest grow on peatland (Ketcheson and Jeglum 1972). Black spruce has a horizontal rooting pattern, with most of the roots occurring in the upper 30 cm, above the water table (Strong and LaRoi 1983). However, the species will root deeper on drier and warmer sites (Tyron and Chapin 1983, Lieffers and Rothwell 1987a). Forest drainage has been shown to increase tree growth by lowering the water table (Payandeh 1973, Stanek 1977, Heikurainen and Joensuu 1981). The resulting improved growing conditions include increased aeration of the rooting zone, higher soil temperatures and increased nutrient cycling (Lees 1972, Kaunisto and Päivänen 1985, Lieffers and Rothwell 1987b).

In a drained area, the optimum depth to water table to improve growth varies between 30 and 60 cm for different tree species (Brække 1983). This optimum is based on the hydrological objective of lowering the water table so that the rooting zone is not under saturated or near-saturated moisture conditions. The major factor that controls the water-table level is ditch spacing (Huikari et al. 1967, Rayment 1970). Widely spaced ditches result in higher water tables than narrowly spaced ditches (Päivänen 1974). Päivänen and Wells (1978) defined two types of spacing: 1) biological, which gives the best growth response, and depends on site-specific factors (e.g., peat type, tree species, precipitation); and 2) economical, which yields the best return on investment, and which is always wider than biological spacing (Seppälä 1972).

The development of spacing guidelines requires research into the ecological changes in peat environments created by drainage. Drainage of forested peatlands to improve tree growth is being investigated in several regions of Canada (Hillman 1987). A project was initiated in 1984 by the Ontario Ministry of Natural Resources (OMNR) in cooperation with Forestry Canada - Ontario Region to study forest drainage and produce spacing and other management guidelines (Koivisto 1985, Rosen 1986a, Jeglum 1991).

The objective of the present study was to characterize water-table profiles between ditches at various spacings in forested and clearcut swamps of the main peatland site types, as determined by the Forest Ecosystem Classification (Jones et al. 1983). These site types, termed "Operational Groups" (OGs), are defined as landscape segments with mature forest that have an identified range of vegetation and soil conditions and related probable responses to specific management prescriptions. Part of the study was originally reported by Berry and Jeglum (1988).

METHODS

Study Area

The Wally Creek Area Forest Drainage Project is located 30 km east of Cochrane, Ontario (Fig. 1), in the Northern Clay Section of the Boreal Forest (Rowe 1972). Climatic data for Cochrane (Anon. 1982a,b,c) show that the area has a continental climate, with cold winters and warm, moist summers. The mean annual temperature is 2°C, with monthly means ranging between -18°C (January) and 17°C (July) and with extremes of

Table 1. Description of site types[a].

Site type	Operational group (OG)	Depth of peat (cm)	Depth of fibric layer (cm)	Bulk density (g/cm^3)		Rooting depth of black spruce (cm)
				0-20 cm	20-40 cm	
Ledum	11	34-174	32	0.0456	0.1479	28
Alnus - herb poor	12	53-250	23	0.0489	0.1468	23
Chamaedaphne (poor treed fen)	14	100-300	30	0.0461	0.1140	33
Chamaedaphne (rich treed fen)	14	300-390	34	0.0688	0.1423	34

[a]For a detailed description of the vegetation, see Jones et al. (1983).

-45°C and 38°C. Approximately 66% of the total annual precipitation of 885 mm occurs as rain. More than 42% of the total occurs as rain from June to September. The remainder is evenly distributed throughout the other months. There is an average of 1328 degree-days (>5°C) per year and potential evapotranspiration (Thornthwaite's method) is estimated to be 490 mm/year (Anon. 1985).

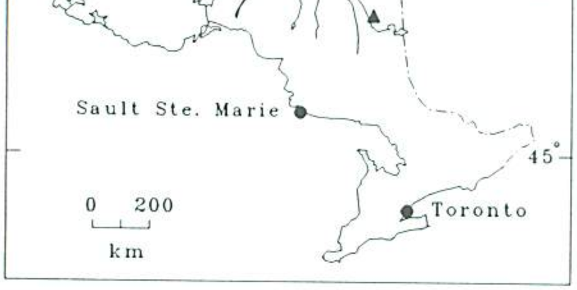


Figure 1. Location of study area (▲) in northeastern Ontario.

The flat topography (slope generally <0.3%) has a natural drainage towards the northwest. The peat is of variable depth (<30 to >300 cm) and overlies a heavy clay of lacustrine origin. The area supports an uneven-aged (50 to 140 yr) 8- to 17-m black spruce swamp stand that has been site-typed according to the Forest Ecosystem Classification (Jones et al. 1983). The study sites are characterized by a black spruce canopy with an understory variously dominated by *Alnus rugosa*, *Ledum groenlandicum*, *Vaccinium myrtilloides* and *Chamaedaphne calyculata*. The moss layer is composed of varying proportions of *Sphagnum nemoreum*, *S. fuscum*, *S. magellanicum*, *S. girgensohnii*, *Pleurozium schreberi* and *Ptilium crista-castrensis*. A general description of the Operational Groups (OGs) studied is given in Table 1.

Drainage Description

The planning and installation of ditches (Fig. 2) in the ca. 450-ha area was done in 1984 to Finnish standards, through the services of an experienced Finnish consultant and machine operators (Koivisto 1985, Rosen 1986b). Spacing of ditches was based on Finnish guidelines for sites equivalent to the OGs in the study. The recommended spacings were 40 to 50 m for OG11 and 30 to 40 m for OG14 (Koivisto 1985). No comparable Finnish equivalent to OG12 was available. The target for depth to water table, as an average across the between-ditch strip, was 40 to 45 cm. Actual ditch spacings ranged from 19 to 80 m in order to verify the applicability of the Finnish recommendations under northern Ontario site and climatic conditions. Almost 72 km of ditches were installed over 280 ha, giving a mean ditch density of 254 m/ha. In most of the area, side ditches averaged 90 cm deep, whereas collector and surround ditches averaged 120 cm deep. The side and surround ditches in the OG14 (rich treed fen) type had to be deeper (approximately 130 cm) because of the thickness of the peat. In the winter of 1984-1985, an adjacent 170-ha area was harvested by clearcutting. The clearcut was divided into three areas, each of which underwent a different form of site preparation before regeneration planting. The three preparations were shearblading, burning and no site preparation (the control). After site preparation, 60 ha was drained in the spring of 1985, with 22 km of ditches, spacings of 12 to 60 m and ditch depths similar to those in the forested area. The resulting ditch density was 368 m/ha.

Measurement of Water-table Levels

Locations for water-table transects (depths measured through a series of wells) were selected from aerial photographs, OG survey maps and ground truthing (Fig. 2). Examples of each of the four OGs listed in Table 1 were located in both drained and undrained forested areas. The clearcut was predominantly a mixture of OG11 and OG12 types, which could not be separated. Both drained and undrained sites were located. The variability of the ditch spacings was reduced by grouping similar spacings in each OG into spacing classes. Some OGs had several classes, whereas others had only one (Table 2). The control class represents the undrained condition.

Water-level wells were constructed of either ABS plastic pipe (3 m long, 5 cm diameter) or steel conduit pipe (1.5 m long, 2 cm diameter). Four holes, 3 mm in diameter, were drilled around the pipe every 10 to 15 cm to within 20 to 40 cm of the well's top. Wells were installed

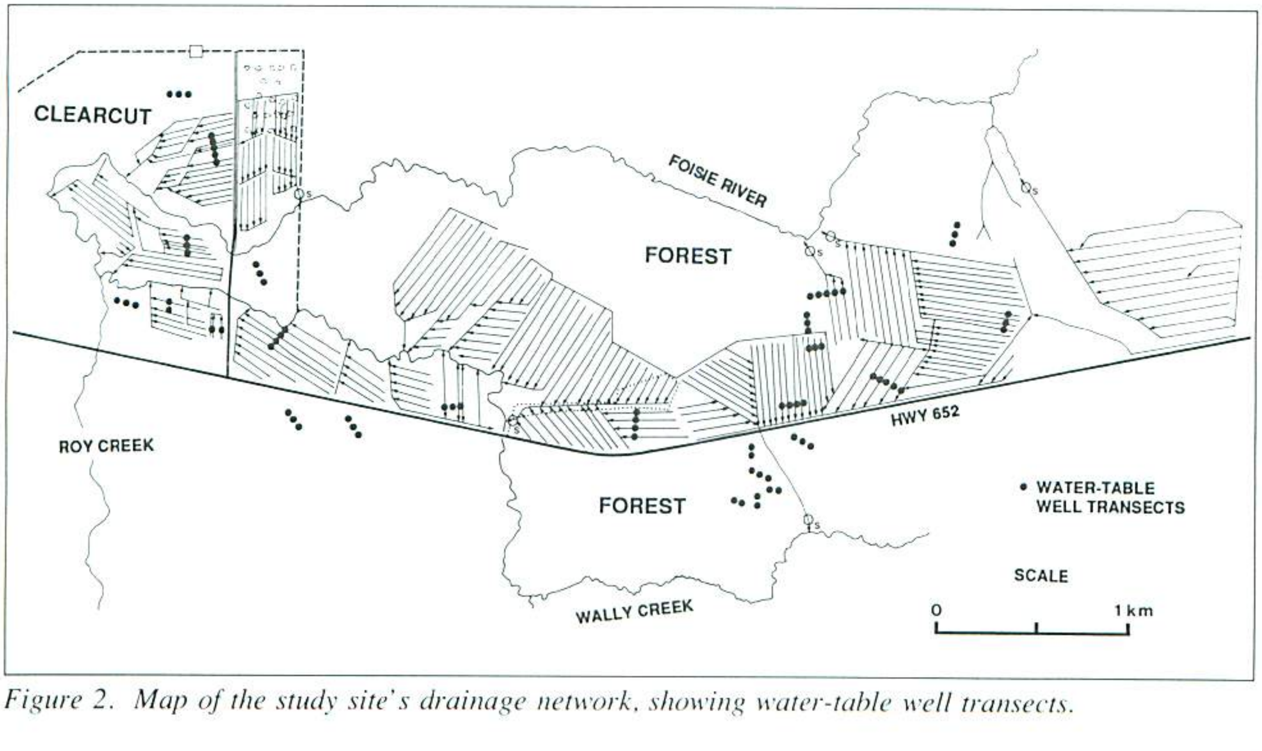


Figure 2. Map of the study site's drainage network, showing water-table well transects.

by one of two methods: 1) by making a hole of similar diameter with an auger, and then inserting the tube in the pre-made hole; or 2) by pushing the tube directly into the peat. The method used was determined by the depth of organic matter at the site. If the depth was less than 130 cm, the first method was used; if greater than 130 cm, then the second (and easier) method was used. In both cases, wells were forced into the underlying mineral soil where possible. Before insertion, the bottom of each well was covered with plastic to prevent soil from filling the well during placement. Once the well was inserted, holes were punched in the plastic to allow for free drainage if the water table dropped below the bottom of the well.

Table 2. Spacing Classes.

Operational group (OG)	Ditch spacing class (m)	No. of wells
FORESTED		
11	25	24
	40	34
	45	28
	60	34
	Control	16
12	35	17
	60T[f]	8
	Control	10
14 (poor)[a]	30	14
	60T[f]	8
	Control	6
14 (rich)[b]	30	20
	Control	5
		Total 224
CLEARCUT		
11/12 (shear)[c]	15	7
	30	7
	60	9
	.Control	10
11/12 (burn)[d]	15	10
	30	13
	Control	10
11/12 (NSP)[e]	15	4
	40	7
	55	9
	Control	10
		Total 96
Total number of wells = 224 + 96 = 320		

[a]poor = poor treed fen
[b]rich = rich treed fen
[c]shear = shearblade site preparation
[d]burn = burning site preparation
[e]NSP = no site preparation
[f]T = transect bounded by one ditch

In the drained areas of both forested and clearcut sites, transects of wells were oriented perpendicular to the ditches. Wells were placed at approximately 5-m intervals along the transects, except for the wells nearest the ditches, which were placed at a distance of 2 m from the ditch center. In addition, two 60-m transects ("60T") were placed perpendicular to a perimeter ditch into an undrained area. One was located in OG12, the other in OG14. In the undrained (control) area, lines of three or five wells were located in representative OG types. In all, 320 wells were established (Table 2).

In October 1986, an intensive survey of all transects (except those in the no-site-preparation area of the clearcut) was done to determine an "average" ground-surface elevation to use as the datum for depth to water table. Measurements were taken at five points near each well: at 0.5 and 1.0 m on both sides along the transect and at the well itself. The mean of these five measurements was then included in a three-point moving-mean procedure to further reduce variability in the peat-surface measurement (cf. Berry and Jeglum 1988). This survey was repeated in October 1989 to detect possible subsidence or growth of the peat surface. The no-site-preparation clearcut transects were surveyed in 1988 only. In October of each year from 1986 to 1989, the elevation of each well in relation to the others in the transect was measured to determine if the wells were subject to frost heaving.

For comparison with the ground survey, hollow and peat-window levels were surveyed to determine if a less variable datum from which to measure depth to the water table could be established (Verry 1984)[1]. The hollow/window levels were found to be independent of the between-ditch-strip gradient. This meant that similar wells (e.g., OG11, 25-m class, 5 m from ditch) could not be used as replicates. As well, it was difficult to relate hollow/window levels to the rooting depth of black spruce. For these two reasons, it was decided that the average peat surface level, as determined by the moving-mean technique, was the best alternative.

Depth to the water table from the top of each well was measured with an electric-buzzer probe activated by contact with the water (Bodley et al. 1989). Depths were measured in 1987, 1988 and 1989, beginning just after the peat thawed and ending with the onset of freeze-up (Table 3). In addition to the regular schedule, depths were measured within 24 hr after storm events. Measurements were taken only during non-storm periods, and were completed in less than 7 hours. This minimized or eliminated any differences in depths as a result of precipitation, evapo-transpiration or drainage that may have occurred during the measurement period. In 1987, a set of measurements was taken at the beginning and end of the 7-hour period and differences in depths were less than 1 cm.

Table 3. Measurement schedule.

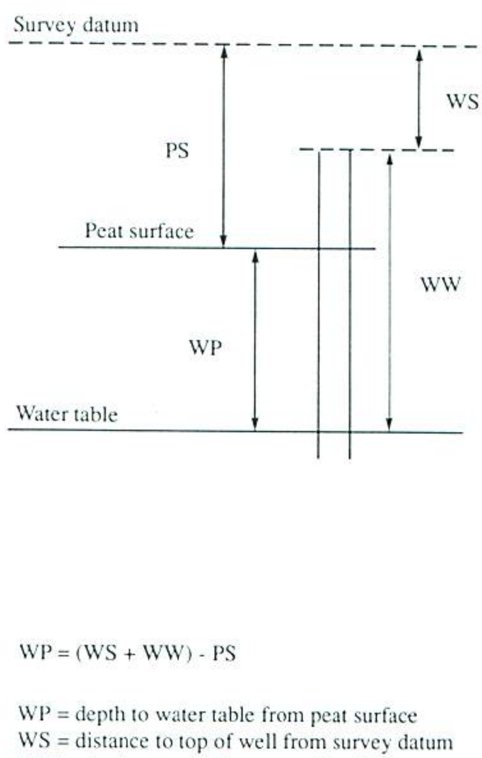
Date	No. measure-ments	Measurement frequency (days)
7 May - 21 Oct. 1987	34	3 - 5
28 May - 16 Oct. 1988	21	4 - 7
24 May - 23 Oct. 1989	17	7 - 9

[1]A peat window is an opening in the living moss layer and is usually filled with water and sometimes with aquatic mosses.

In October 1986, measurements were also taken of peat depth at each well, rooting depth of black spruce, depth of the fibric layer and bulk densities of the peat at depths of 0 to 20 cm and 20 to 40 cm (Table 1). An automated weather station measured hourly total precipitation.

Data Analysis

The peat-surface and well-survey data, together with the probe measurements, were used to calculate depth to water table below the moving-mean peat surface. The procedure involved adding or subtracting survey or depth data, as shown in Fig. 3. The results were then grouped according to year, OG, spacing class and distance of the well from the ditch.



$$WP = (WS + WW) - PS$$

WP = depth to water table from peat surface
WS = distance to top of well from survey datum
WW = depth to water from top of well
PS = distance to peat surface from survey datum

Figure 3. Method of calculating depth to water table from the surface of the peat.

The seasonal mean depth to water table (seasonal refers to the entire field season) was analyzed by means of a general linear model procedure for analysis of variance to produce a Student-Newman-Keuls test for multiple comparison of means ($p=0.05$). This analysis technique was used to compare depths to the water table from the peat surface in the following categories:

1) Among years for the same OG, spacing class, and distance from ditch. For example, for OG11, 40-m spacing class, and at a distance of 2 m from the ditch, the comparison was 1987 vs. 1988 vs. 1989.

2) Each year, for the same OG and spacing class, comparisons were made among the various distances from the ditch. For example, for 1987, OG11 and a 40-m spacing class, comparisons were made among 2 m vs. 5 m vs. 10 m vs. 15 m from the ditch vs. at the center of the spacing.

3) Each year, for the same OG and same distance from the ditch, comparisons were made among spacing classes. For example, for 1987, OG11, and 2 m from the ditch, comparisons were made among the 25-, 40-, 45- and 60-m spacing classes.

4) Each year, comparisons were made among OGs for similar spacing classes and distances from the ditch. For example, for 1987 at 2 m from the ditch, comparisons were made among the OG11-25 m, OG11-40 m, OG12-35 m, and OG14-30 m classes.

To account for possible changes in peat surface levels over time, the first comparison was repeated on the basis of depths to water table from an arbitrary survey datum above the peat surface (i.e., WS+WW; see Fig. 3). Because the transects were not surveyed in relation to each other, spacing classes could not be used. Instead, the analyses were done on an individual-spacing basis. The results from this could not be related directly to those of the first comparison because of the different spacings. Another repetition was done with data on depth to water table from the peat surface from individual spacings. In all, 619 tests were made.

Hydraulic conductivity (K) was calculated from the bulk-density (D_b) measurements using the regression equation determined by Boelter (1969), where:

$$\log K = -1.589 - 16.086 D_b \,,\ r^2 = 0.54$$

Weekly total precipitation was obtained from the weather-station data. The distribution of weekly totals were compared between years by using one year as a base value and subtracting it from the others (i.e., 1988-1987, 1989-1987 and 1989-1988). The differences were then plotted to show periods of wet and dry conditions.

RESULTS AND DISCUSSION

Differences Among Years

Mean seasonal depths to water table from the arbitrary survey datum were not significantly different among years for 74% of the wells (Table 4). Only 3% of depths differed among all

Table 4. Summary of the results of Student-Newman-Keuls tests, among years.

Significance	Depth (cm) from		
	Peat surface[a]	Peat surface[b]	Datum[b]
	- - - % of total tests - - -		
No. sig. diff.	42	55	74
All years sig. diff.	7	7	3
1987 sig. diff. (driest)	39	27	1
1989 sig. diff. (driest)	7	4	16

[a]by spacing class
[b]individual spacings

Table 5. Monthly and seasonal total precipitation. (20 May - 12 Oct.)

	Total precipitation (mm)					
Month	1987	%N[a]	1988	%N[a]	1989	%N[a]
May	54	ND	23	ND	63	ND
June	80	87	86	93	81	88
July	104	107	30	31	66	67
Aug.	94	110	159	185	108	126
Sept.	60	59	113	111	71	70
Oct.	42	ND	29	ND	27	ND
Total	434		440		416	
Mean		91		105		88

[a]%N = percentage of 30-year monthly mean precipitation
(ND = no data)

Table 6. Frequency of measurements of depth to water table during wet and dry periods[a].

Years compared	No. weeks		No. weeks measured		No. measure-ments	
	Wet	Dry	Wet	Dry	Wet	Dry
1988 - 1987	8	10	6[b]	7	8[c]	8
1989 - 1987	7	8	5	7	5	8
1989 - 1988	6	9	4	7	5	7

[a]wet = wetter than average, dry = drier than average, both by ≥ 10 mm (based on data in Fig. 4)
[b]Example: measurements were made in 6 of the 8 wet weeks
[c]Example: 8 measurements were made during the 8 wet weeks

three years, but 16% of depths were lowest in 1989. This similarity among years was the result of two factors. First, the total seasonal precipitation was similar, ranging from 416 mm in 1989 to 440 mm in 1988 (Table 5). Second, although the distribution of the total precipitation varied among years (Fig. 4 and Table 5), there was an approximately equal sampling during wet and dry periods in each year (Table 6). The greater depths to water table that were measured in 1989 for 16% of measurements (Table 4) were probably a result of reduced precipitation (88% of normal, compared with 91% and 105% for 1987 and 1988, respectively; Table 5).

When the peat surface was used as the reference datum, the number of wells with no significant differences in depth among years decreased to 55% (Table 4). As well, depths in 1989 were lowest for only 4% of wells, and 1987 depths were lowest in 27% of the wells. The differences in the results between using the survey datum and the peat-surface datum indicate that the level of the peat surface changed over time. This change could be a result of either growth or subsidence of the peat, or measurement error associated with the two peat-surface surveys. The peat-surface height decreased (i.e., subsided) by from 1 to 10 cm in most areas, and increased by 2 cm in only two cases (Table 7). Boelter (1972) measured subsidence of 3 to 6 cm within 3 years in a black spruce/*Sphagnum* site on which the water table was maintained at 30 to 60 cm below the peat surface. The values may be comparable with those of the present study, but the fact that the peat surface height decreased by from 2 to 5 cm in five of the seven undrained controls in the present study, when peat growth was expected, suggests that survey measurement error was the cause of any differences. The higher peat levels in 1987 accounted for the high percentage of greater depths to water table.

Although the seasonal mean depths to water table were similar among years, the timing of the occurrence of high and low levels differed, depending on the amount and distribution of precipitation (Fig. 5). In 1987, minimum depths occurred in early June, when the soil was wet from snowmelt and subsequent heavy rainfall. Maximum depths occurred in early September, after 5 weeks of low rainfall and high evapotranspirational demands. Individual precipitation events of less than 10 mm did not affect the water table during dry periods because all the rain was used to satisfy moisture requirements in the upper, unsaturated layer. The fibric layer, with its large pores, has a saturated volumetric water content of more than 90% (Boelter 1969). In 1988, a series of major midsummer storms caused water tables to reach their highest levels in mid-August. These storms followed a 4-week dry period, during which the

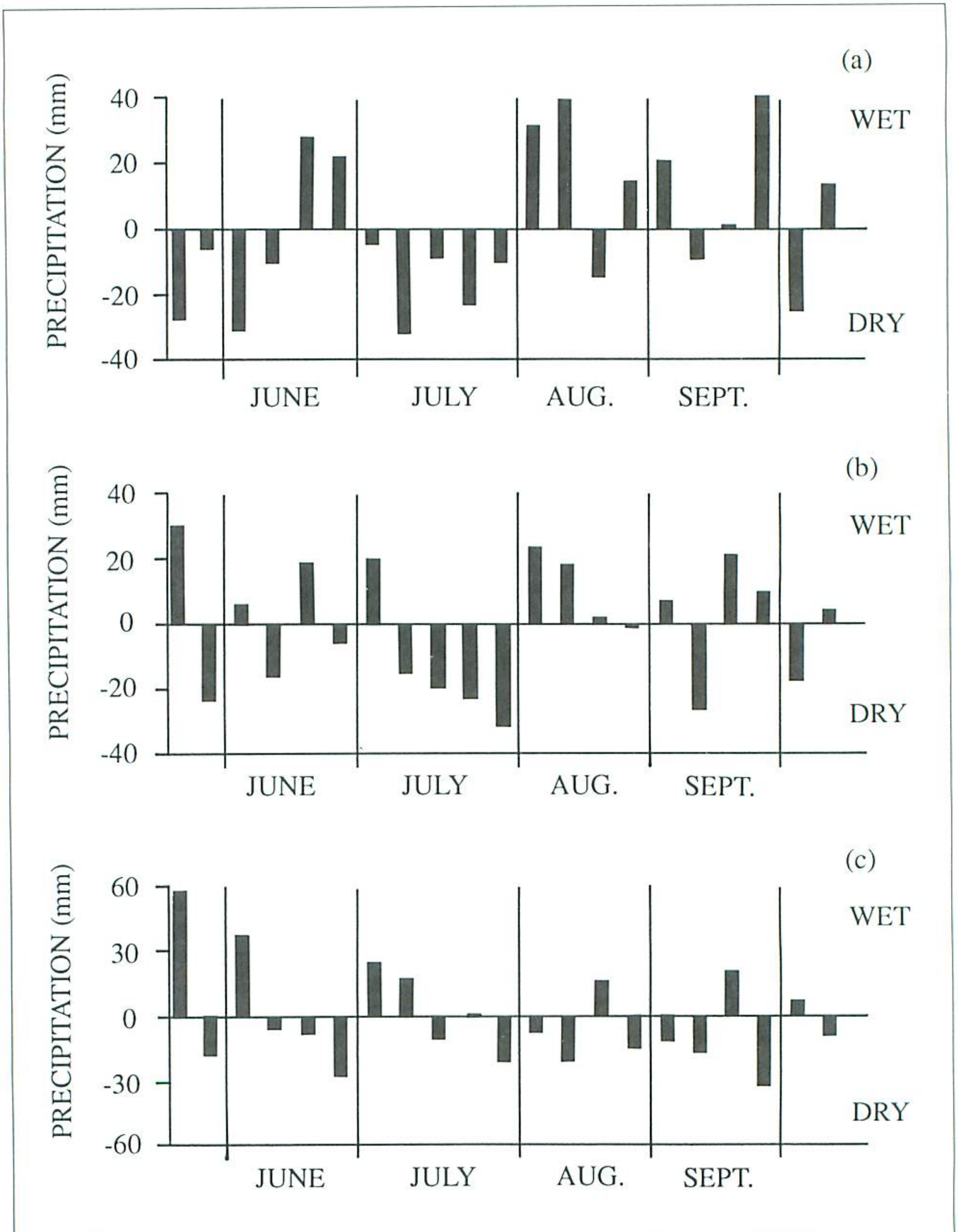


Figure 4. Comparisons of the distribution of weekly total precipitation: (a) 1988 - 1987, (b) 1989 - 1987 and (c) 1989 - 1988.

maximum depths to water occurred. In 1989, minimum depths to water occurred after a major storm event in mid-May, when the soil was still wet from snowmelt. Maximum depths to water occurred at the end of a 2-week dry period in July. Depths to water were also quite large during the second week of September 1989. By comparing the timing of minimum and maximum depths in relation to weekly total precipitation (Fig. 5) with normal precipitation values (Table 5), we estimated that 1987 was the more typical of the 3 years in terms of when minimum and maximum depths to water can be expected to occur.

Table 7. Changes in peat surface levels from 1986 to 1989.

OG	Spacing class (m)	Mean decrease or (increase) (cm)
FORESTED		
11	25	7
	40	4
	45	5
	60	5
	Control	3
12	35	(2)
	60T	1
	Control	5
14(rich)	30	5
	Control	2
14(poor)	30	5
	60T	5
	Control	(2)

Site prep.	Spacing class (m)	Mean decrease (cm)
CLEARCUT		
Burned	15	8
	30	10
	Control	3
Shearbladed	15	7
	30	7
	60	5
	Control	3
None	15	ND[a]
	40	ND
	55	ND
	Control	ND

[a]ND = no data

Grouping the individual spacings into spacing classes caused the percentage of wells with no significant difference among years to decrease by a further 13% (to 42%), while increasing the number of wells with greater depths in 1987 by 12% (to 39%) (Table 4). These changes were the result of greater variability in depths as a result of the grouping process. Regardless of these changes, the relationships among OGs, among spacing classes and among distances from the ditch remained the same from year to year. The statistical results, therefore, were also consistent from year to year and are summarized in Tables 8 to 12.

Differences Among Distances from the Ditch

Examples of water-depth profiles between ditches for selected individual spacings are illustrated in Figures 6 to 9. The water-table profiles in the >30-m spacings (e.g., Fig. 7) have an elliptical shape (Brække 1983, Hillman 1988) that is the result of differing soil-water potentials within the peat caused by the ditches (Hillel 1982). The <30-m spacings (Fig. 6a and 9a) tended to have a much flatter water-table profile than did the wider spacings. In all cases, the shape of the water-table profile was independent of the peat-surface hummocks and hollows.

Within each spacing class of each OG, the elliptical shape indicated that depth to water decreased as distance from the ditch increased (Fig. 10 to 12). Mean depths for the 3 years at

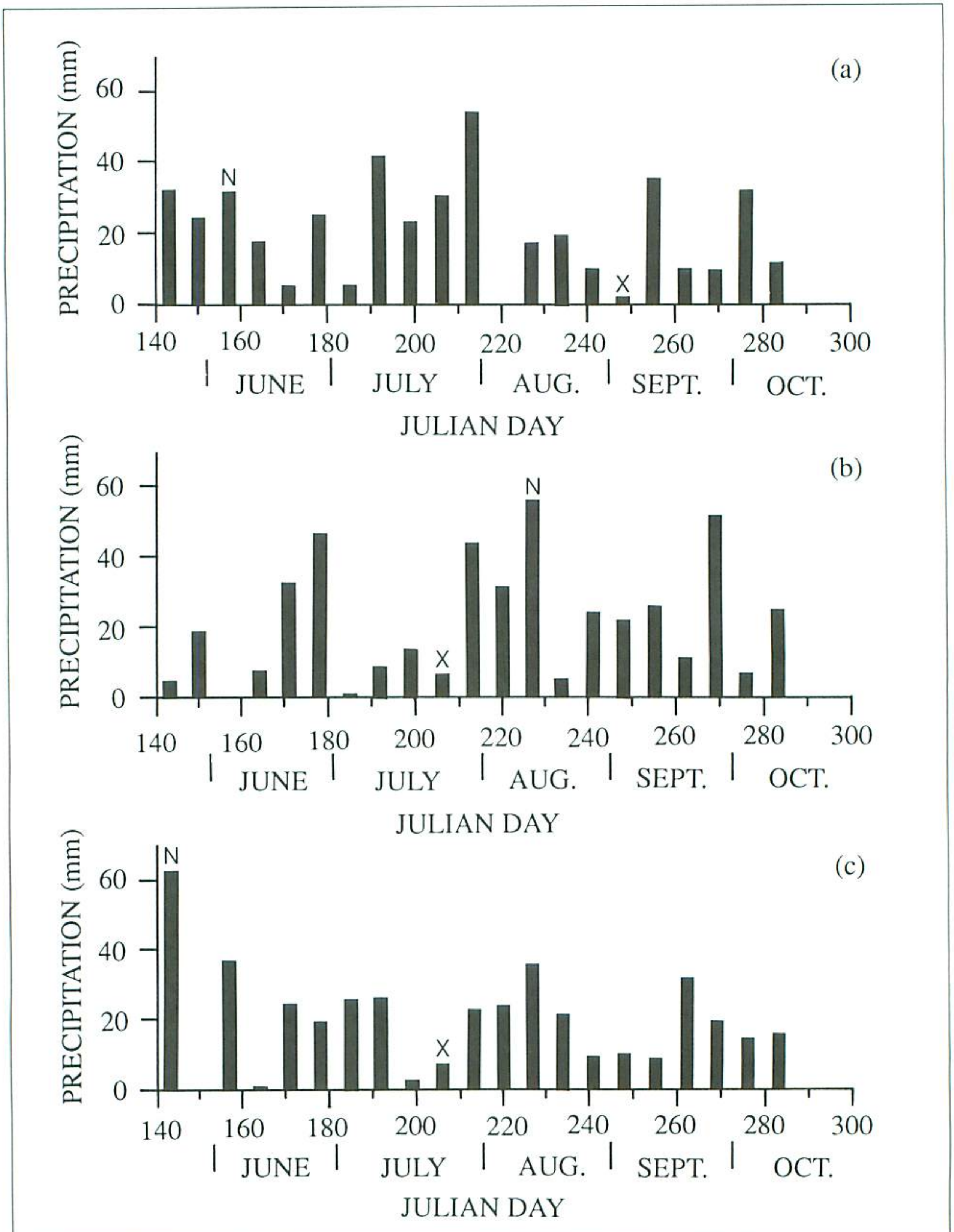


Figure 5. Weekly total precipitation for (a) 1987, (b) 1988 and (c) 1989. Minimum (N) and maximum (X) water-table depths are also shown.

Table 8. Student-Newman-Keuls test result formats for data in Tables 9-12.

Among distances from ditch (Table 9): OG11, 40-m spacing class

SNK results[a]:	2 m	deepest water table
	5 m	
	10 m	
	15 m, Center	
	Control	shallowest water table

2 m from ditch ≠ 5 m ≠ 10 m ≠ (15 m = center) ≠ control

Among spacing classes (Table 10): OG11, 2 m from ditch

SNK results[a]:	25 m	deepest water table
	40 m, 45 m	
	60 m	
	Control	shallowest water table

25-m spacing class ≠ (40-m = 45-m) ≠ 60-m ≠ control

Among OGs (Table 11): Forested OG11-25 m vs. OG11-40 m vs. OG12-35 m vs. OG14P-30 m vs. OG14R-30 m, 5 m from ditch

SNK results[a]:	OG14R-30 m	deepest water table
	OG12-35 m	
	OG11-25 m, OG11-40 m	
	OG14P-30 m	shallowest water table

OG14R-30 m spacing class ≠ OG12-35 m ≠ (OG11-25 m = OG11-40 m) ≠ OG14P-30 m

Among OG controls (Table 12):

SNK results[a]:	OG11	deepest water table
	OG12	
	OG14P	
	OG14R	
	no site prep.	
	shearbladed, burned	shallowest water table

OG11 ≠ OG12 ≠ OG14P ≠ OG14R ≠ no site prep. ≠ (shearbladed = burned)

[a]Values on different lines are significantly different at p=0.05.

Table 9. Summary of the results of Student-Newman-Keuls tests for comparisons among distances from ditches.

Spacing class (m)	Distance from ditch[a] (m)
FORESTED	
OG11	
25	2
	5, 10
	Center
	Control
40	2
	5
	10
	15, Center
	Control
45	2
	5
	10, 15, 20, Center, Control
60	2
	5, 10, 15, 20, 25, Center, Control
OG12	
35	2
	5
	10, 15, Center
	Control
60T	2
	5
	10
	15
	20, 25, 30, 40, 50, 60, Control
OG14P	
30	2
	5
	10, Center
	Control
60T	2
	5
	10
	15
	20, 25, 30, 40, 50, 60, Control
OG14R	
30	2
	5, 10, Center
	Control

Spacing class (m)	Distance from ditch[a] (m)
CLEARCUT	
Shearbladed	
15	2
	5, Center
	Control
30	2
	5
	10, Center
	Control
60	2
	5, 10, 15, 20
	25
	Center, Control
Burned	
15	2
	5, Center
	Control
30	2
	5, 10
	Center
	Control
No site prep.	
15	2, 5, Center
	Control
40	2
	5, 10, 15
	15, Center
	Control
55	2
	5, 10, 15, 20, 25, Center, Control

[a]Values on different lines are significantly different at $p=0.05$.

Table 10. Summary of the results of Student-Newman-Keuls tests for comparisons among spacing classes.

Distance from ditch (m)	Spacing class[a] (m)
FORESTED	
OG11	
2	25
	40, 45
	60
	Control
5	25, 40
	40, 45
	60, Control
10	25
	40
	45
	60, Control
15	40, 45
	Control
	60
20	45, 60, Control
center	25
	40, 45, 60, Control
OG12	
2	35, 60T
	Control
5	35, 60T
	Control
10	35, 60T
	Control
15	35, 60T
	Control
OG14P	
2	30
	60T
	Control
5	30
	60T
	Control
10	30
	60T
	Control
CLEARCUT	
Shearbladed	
2	15, 30
	60
	Control
5	15, 30
	60
	Control
10	30, 60
	Control
center	15, 30
	60, Control
Burned	
2	15, 30
	Control
5	15, 30
	Control
center	15
	30
	Control
No site prep.	
2	15
	40
	55
	Control
5	15
	40
	55
	Control
10	40
	55, Control
15	40
	55, Control
center	15
	40
	55, Control

[a]Values on different lines are significantly different at p=0.005.

Table 11. Summary of results of Student-Newman-Keuls tests for comparisons among operating groups[a].

(a) FORESTED: OG11-25 m vs. OG11-40 m vs. OG12-35 m vs. OG14P-30 m vs. OG14-30 m

Distance from ditch (m)	Condition and spacing class
2	OG14R-30 m
	OG12-35 m, OG14P-30 m
	OG14P-30 m, OG11-25 m
	OG11-40 m
5	OG14R-30 m
	OG12-35 m
	OG11-25 m, OG11-40 m
	OG14P-30 m
10	OG14R-30 m
	OG11-25 m
	OG12-35 m, OG14P-30 m, OG11-40 m
15	OG12-35 m, OG11-40 m
center	OG14R-30 m
	OG11-25 m
	OG12-35 m, OG14P-30 m, OG11-40 m

(b) FORESTED VS. CLEARCUT: OG11-25 m vs. N-15 m vs. S-15 m vs. B-15 m

Distance from ditch (m)	Condition and spacing class
2	N-15 m
	F-25 m
	S-15 m, B-15 m
5 and center	N-15 m
	F-25 m
	S-15 m
	B-15 m

(c) FORESTED VS. CLEARCUT: OG11-25 m vs. OG12-35 m vs. S-15 m vs. B-15 m

Distance from ditch (m)	Condition and spacing class
2 and 5	F-35 m
	F-25 m
	S-30 m
	B-30 m
10 and center	F-25 m
	F-35 m
	S-30 m, B-30 m

(d) FORESTED VS. CLEARCUT: OG12-35 m vs. OG-40 m vs. N-40 m

Distance from ditch (m)	Condition and spacing class
2 and 5	F-35 m
	F-40 m, N-40 m
10	F-35 m, F-40 m
	F-40 m, N-40 m
15 and center	F-35 m, F-40 m, N-40 m

(e) FORESTED VS. CLEARCUT: OG11-60 m vs. S-60 m vs. N-55 m

Distance from ditch (m)	Condition and spacing class
2	F-60 m
	S-60 m, N-55 m
5 to 15	F-60 m, S-60 m
	N-55 m
20 and 25	F-60 m
	S-60 m
	N-55 m
center	F-60 m
	S-60 m, N-55 m

[a]Values on different lines are significantly different at p=0.05

N = no site preparation

S = shearbladed

B = burned

F = forested

distances of 2 m from a ditch ranged from 35 cm (OG11/12, clearcut, no site preparation, 55-m spacing) to 80 cm (OG14, rich treed fen, 30-m spacing) (Tables 13 and 14). Depths at spacing centers varied between 19 cm (OG11/12, clearcut, no site preparation, 55-m spacing) and 72 cm (OG14, rich treed fen, 30-m spacing). Differences in depths between the 2-m distance and the spacing center ranged from 1 cm (OG11/12, clearcut, no site preparation, 15-m spacing) to 25 cm (OG12, 35-m spacing).

The results of the Student-Newman-Keuls tests show that the water table often reached a constant depth within 5 to 10 m of a ditch (Table 9). Depths similar to those of the controls (i.e., undrained areas) were achieved only by spacings ≥45 m at distances from a ditch ranging from 5 m (OG11, 60-m spacing) to approximately 30 m (OG11/12, clearcut, shearbladed, 60-m spacing). Two exceptions to this were the 60-m transects bounded by only one ditch (i.e., 60T). In these cases, a constant water-table depth was not reached until 20 m from the ditch, at which point the water table was near the level of the control water table (Fig. 10b and 11).

Differences Among Spacing Classes

For a given distance from a ditch, the depth to water decreased as ditch spacing increased (Fig. 10-12 and Table 10). This common effect has been noted by Päivänen (1974) and Päivänen and Wells (1978). The OG11 mean depths to the water table at 10 m from a ditch ranged from 48 cm for the 25-m spacing to 35 cm for the 60-m spacing (Table 13). The no-site-preparation clearcut had water-table depths between 65 cm for the 15-m spacing and 27 cm for the 55-m spacing at 5 m from a ditch (Table 14). These differences show that the soil-water potentials, which control the horizontal movement of water into the ditches, were such that shallower water tables were maintained at wider ditch spacings.

Table 12. Summary of the results of Student-Newman-Keuls tests for comparisons among the controls for each operating group[a].

FORESTED AND CLEARCUT	
	OG11
	OG12
	OG14P
	OG14R
no site prep.	(OG11/OG12 clearcut)
burned, shearbladed	(both OG11/OG12 clearcut)

[a]Values on different lines are significantly different at p=0.05.

The results of the Student-Newman-Keuls tests indicated that it was not possible in most cases to assume that depth to water at a given distance from a ditch at a wide spacing would be equivalent to that at the center of an equivalent spacing. For instance, depth at 10 m from a ditch in the OG11 60-m spacing class was not equal to depth at the approximate center of the 25-m class (Tables 10 and 13). Similarily, the 60T transects could not be assumed to represent 120-m spacings because of the inflow of water from the undrained areas.

Differences Among Operational Groups

Among the forested OGs, depths to water at 2 and 5 m from a ditch for the OG14R, 30-m spacing and OG12, 35-m spacing were greater than for the OG11, 25-m spacing and OG11, 40-m spacing (Table 11a). At distances greater than 5 m, the OG12, 35-m spacing had depths less than those of the OG11, 25-m spacing, but similar to those of the OG11, 40-m spacing. The depth of peat overlying the heavy clay may explain why the water table of the OG12, 35-m spacing rose significantly more between 2 and 10 m from the ditch than did the water tables in the OG11, 25-m spacing and the OG11, 40-m spacing (Table 11a). Peat depths in the two OG11 spacing classes were only 50 and 61 cm, respectively, compared with 243 cm for OG12 (Table 15). The hydraulic conductivity of the peat in both OGs in the upper 40 cm was a minimum of 2.1 X 10^{-4} cm/s (Table 16), versus

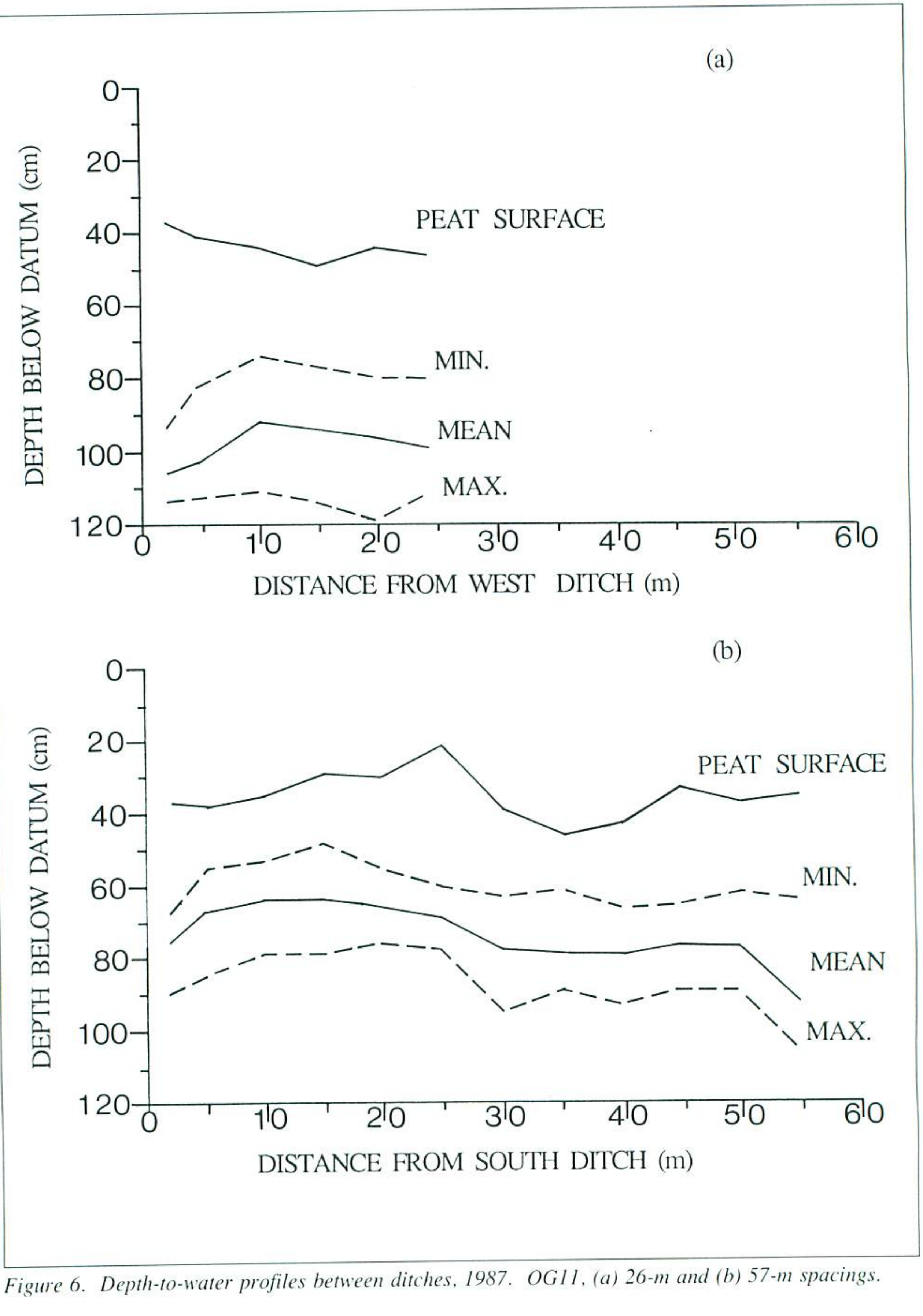


Figure 6. Depth-to-water profiles between ditches, 1987. OG11, (a) 26-m and (b) 57-m spacings.

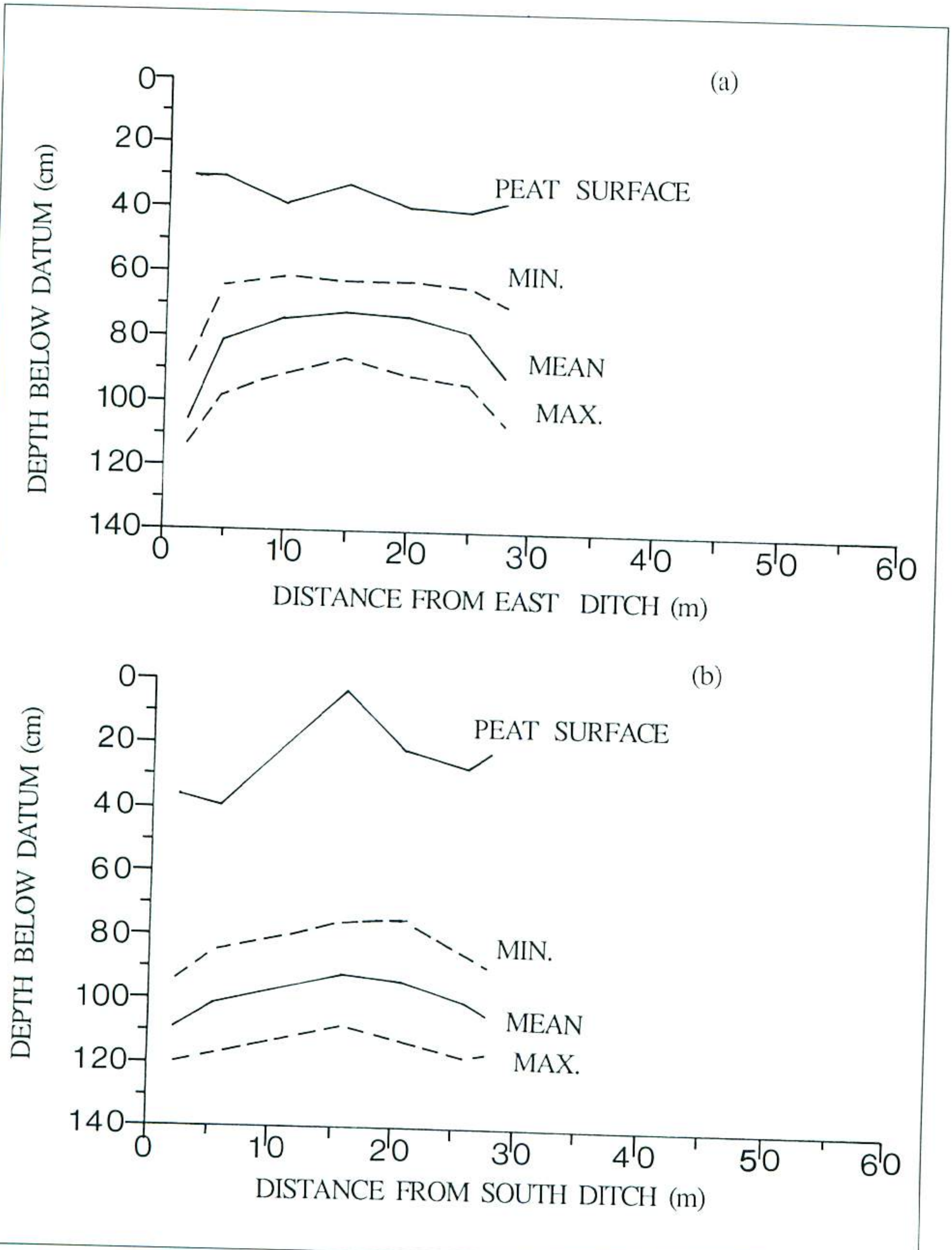


Figure 7. Depth-to-water profiles between ditches, 1987. OG14, poor (a) and rich (b) treed fens, 30-m spacings.

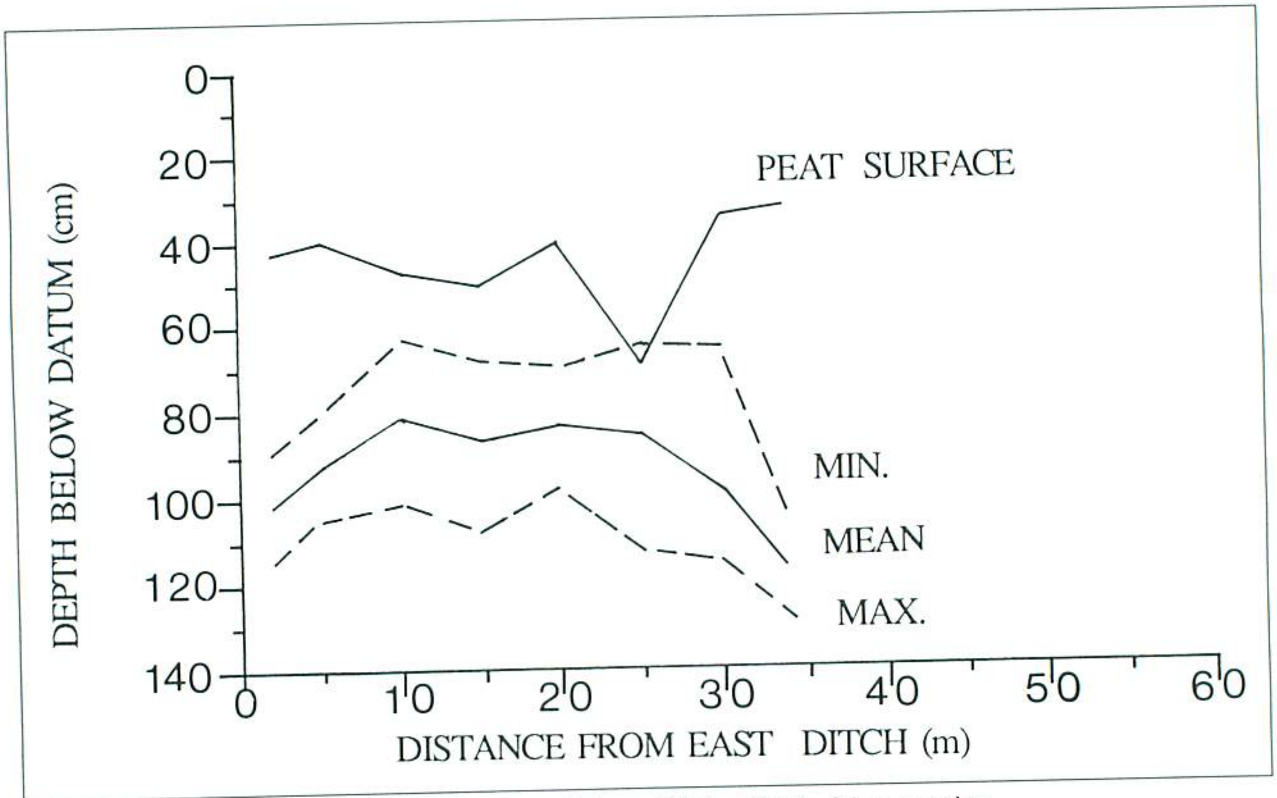


Figure 8. Depth-to-water profiles between ditches, 1987. OG12, 36-m spacing.

an estimated 0.01 X 10^{-4} cm/s for the clay (Anon. 1978). In OG11, water may have been held above the boundary separating the vastly different conductivities of the peat and clay (Hillel 1982), which would have maintained a higher water table closer to the ditch. As distance from the ditch increased, this controlling factor became less important compared with spacing-influenced soil-water potentials, and the water table in both OGs reacted similarily.

The two OG14 fens had significantly different depths to the water table for all distances from the ditch, even though spacing was the same (Table 11a and Fig. 10). The rich treed fen had water-table depths 18 to 34 cm greater than those of the poor treed fen (Table 13). Depth of peat exceeded 100 cm at both sites and could not be considered a source of variation. The variation in these results was probably not a result of evapotranspirational differences because the rich treed fen had only a sparse tree cover, whereas the poor treed fen had a continuous cover. However, the peat profiles and the character of the microtopography differed strongly among the sites. The rich fen had a deeper layer of loosely compacted, fibric *Sphagnum* peat overlying a mesic, more decomposed peat, than did the poor fen. Thus, the water table tended to lie deeper beneath the surface in the rich fen because the mesic, poorly drained peat layer was further beneath the surface.

Another major difference between the sites that could have accounted for the different water-table depths was the greater ditch depth of the rich treed fen (130 cm) versus that of the poor treed fen (90 cm). Heikurainen (1980) suggested that ditch depth was more important than spacing in controlling depth to water table. At spacings of 32 to 90 m, he found that a 10-cm increase in ditch depth would lower the water table at the spacing center by 3 cm. Other studies, however, indicated that spacing was more effective than ditch depth in controlling water-table levels (Burke 1969, Rayment 1970, Päivänen and Wells 1978). Huikari et al. (1967) observed that the relationship between ditch depth and spacing as

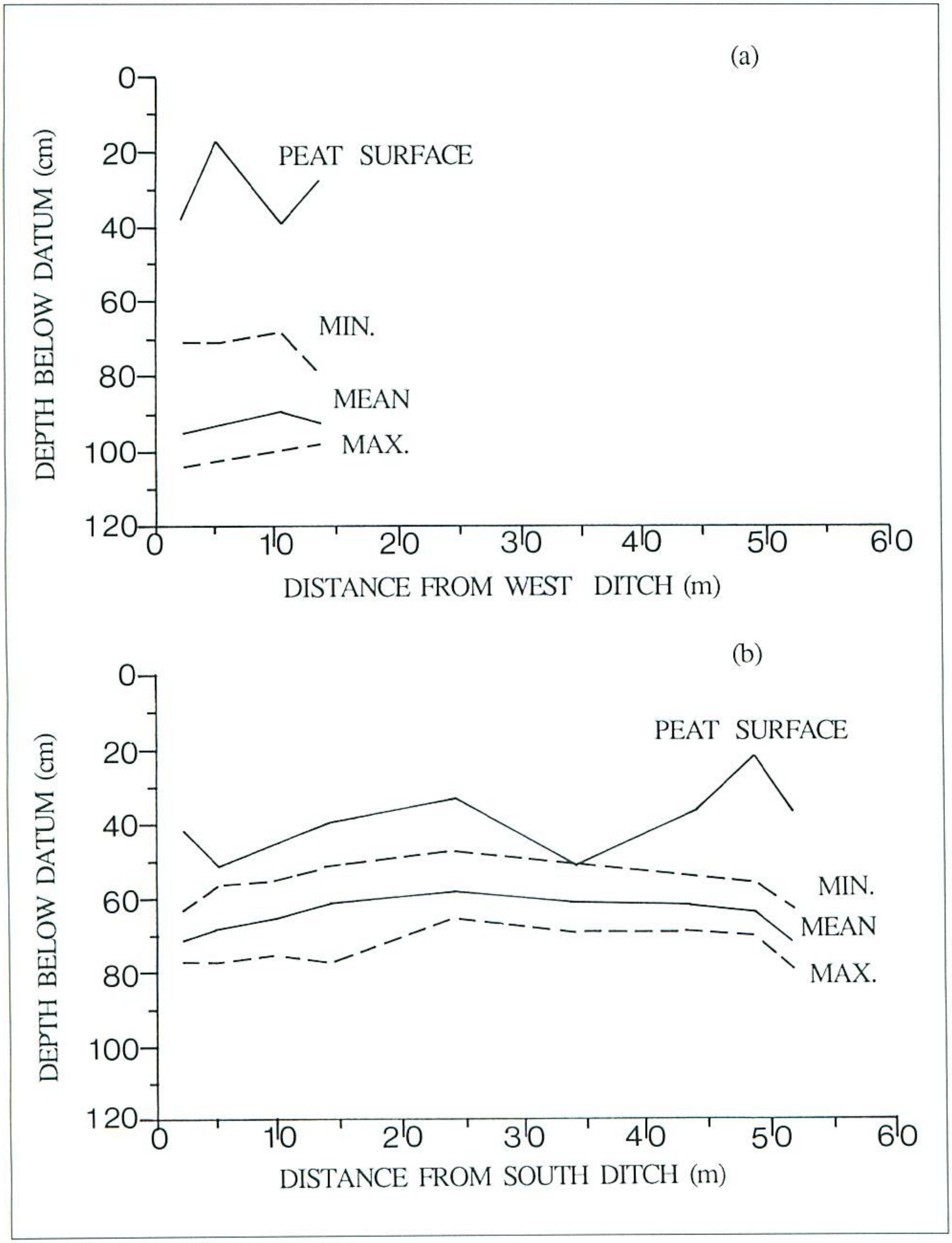


Figure 9. Depth-to-water profiles between ditches, 1987, OG12, harvested site with no site preparation. (a) 16-m and (b) 54-m spacings.

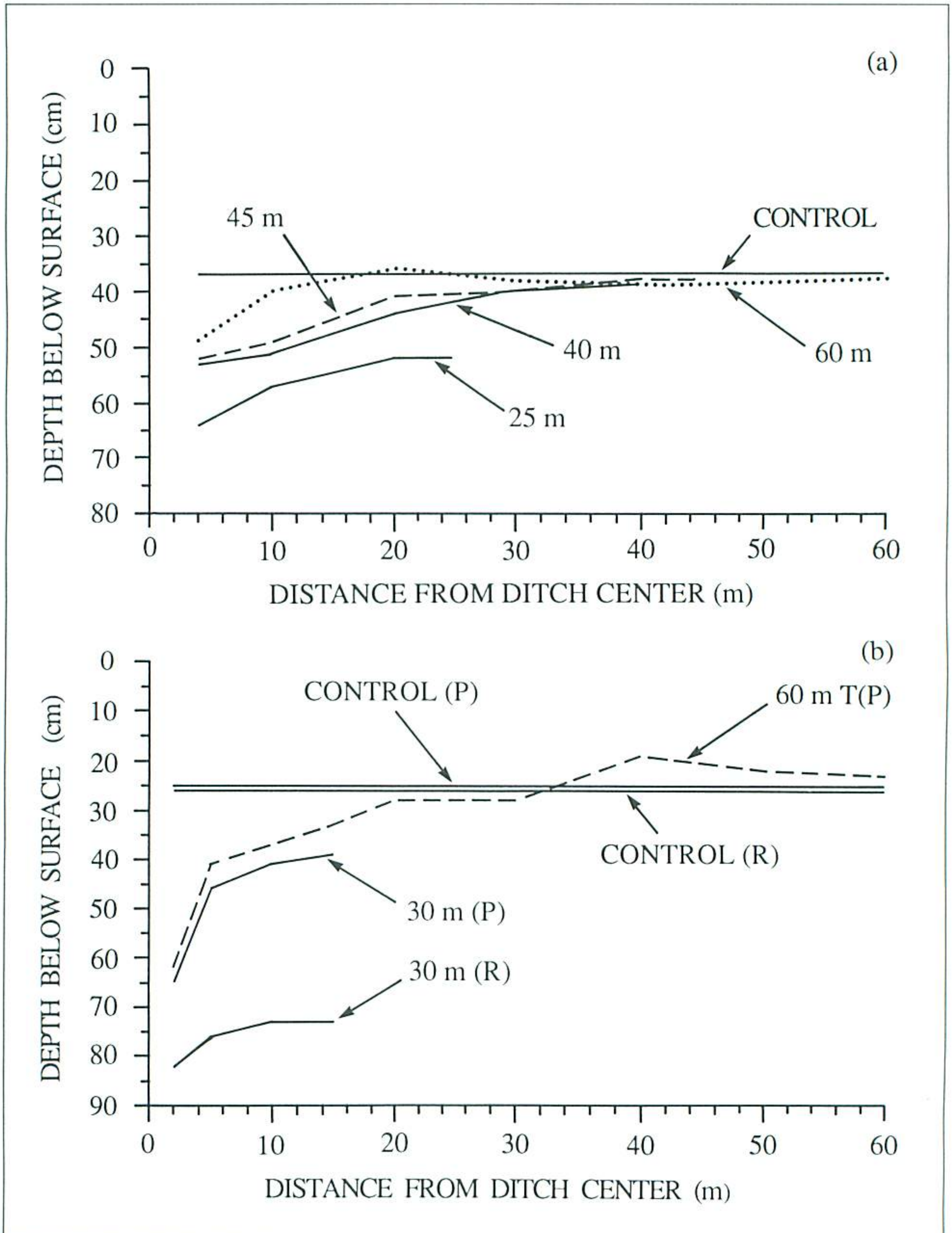


Figure 10. Depth-to-water profiles: 1987 seasonal means, by spacing classes, for (a) OG11 and (b) OG14 rich (R) and poor (P) treed fens.

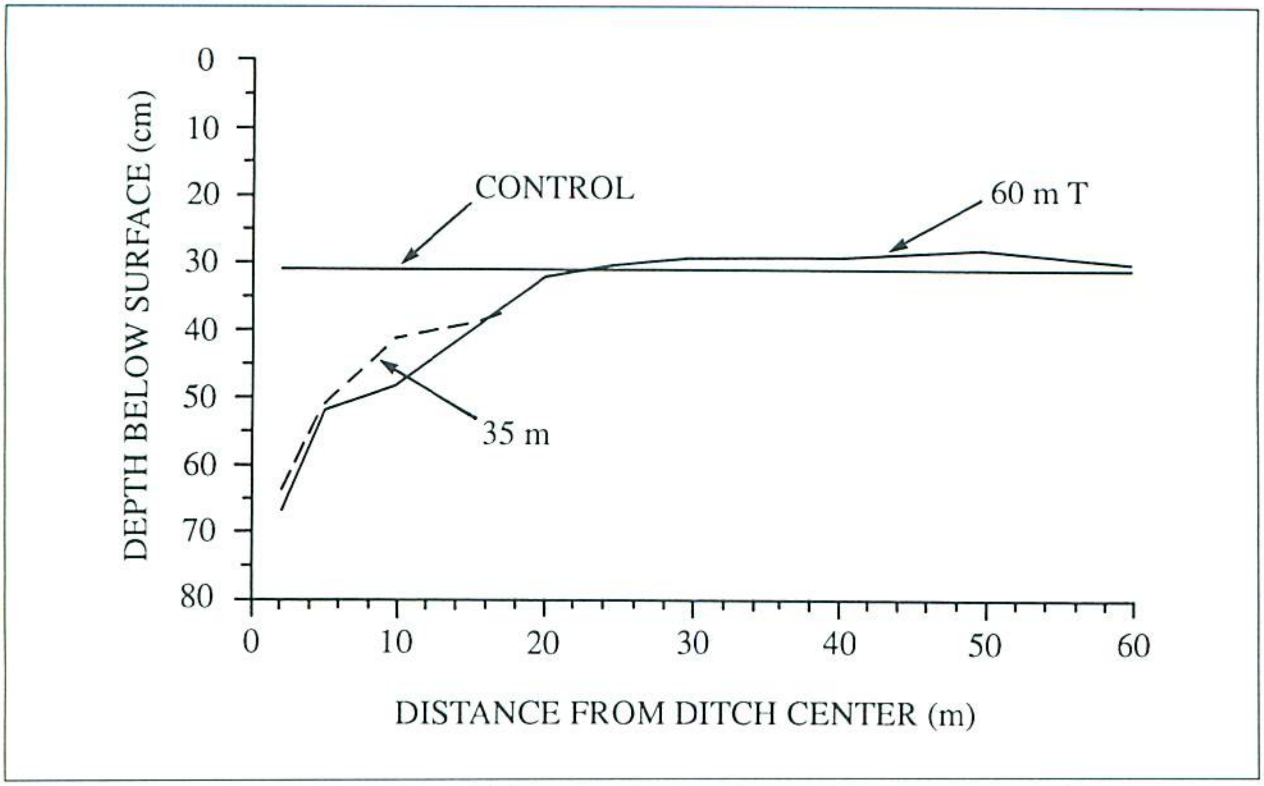


Figure 11. Depth-to-water profiles: 1988 seasonal means, by spacing classes, for OG12.

controlling factors depended on the width of spacing. Ditch depth was most important when spacing was ≤20 m, spacing was most important when it was 30 to 60 m, and depth and spacing had equal influence when spacing was >60 m.

Harvesting caused a significant rise in the water table, both in drained and undrained areas (Tables 11b-e and 12). Higher water tables after harvesting are attributable to a combination of decreased interception of precipitation by vegetation (Heikurainen and Päivänen 1970) and decreased evapotranspiration as a result of loss of the vegetation canopy (Hewlett 1982). Depths to water table in the harvested OG11/OG12 controls were 0 to 18 cm less than in the forested OG11/OG12 controls (Tables 13 and 14). Depths to water table at spacing centers in the drained area were 2 to 17 cm less in the harvested area than in the forested area for comparable spacing classes (Tables 13 and 14). The similarity of these increases suggests that drainage did not reduce the magnitude of the water-table rise after harvesting.

Site preparation had an effect on depth to water table. The shearbladed and burned areas had higher water tables than the no-site-preparation area at the 15-m spacing and, by comparison with OG12, 35-m spacihg and non-site-prepared 40-m spacing, at the 30-m spacings (Table 11b,c,d). The 55- and 60-m spacings had no differences in water-table depths at the spacing centers as a result of site preparation (Table 11e). Both site-preparation techniques involved removing a portion of the fibric layer of the peat. This removal resulted in lower peat surfaces in relation to peat depth, a thinner fibric layer over the mesic and humic layers, and decreased evapotranspiration from the peat. These conditions would cause decreased depths to water from the peat surface at the narrower spacings, especially for OG11, with its thin peat layer. The similarity in depths to the water table at the wide spacings (Table 11e) suggests that the availability of water in the no-site-preparation area was greatly in excess of evapotranspirational capacity, resulting in a high water table comparable to that in the shearbladed area.

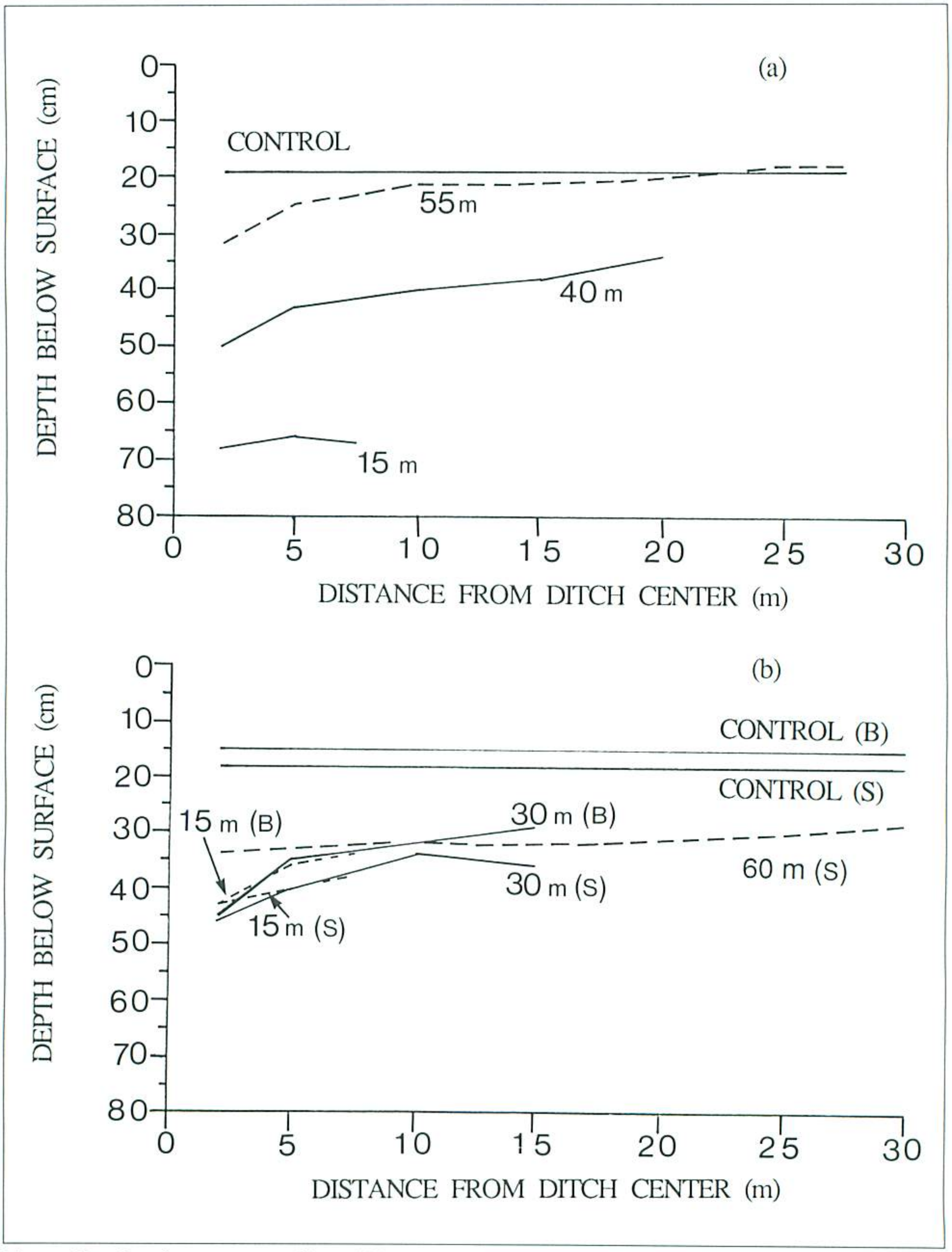


Figure 12. Depth-to-water profiles: 1987 seasonal means, by spacing classes, for harvested OG12. (a) no site preparation, (b) shearbladed (S) or burned (B).

Table 13. Mean (3-year) seasonal depths to the water table - forested sites. (Detailed results are presented in Appendices 1-5.)

Spacing class (m)	Distance from ditch (m)	Water-table depth (cm)
<u>OG11</u>		
25	2	62
	5	51
	10	48
	center	44
40	2	53
	5	48
	10	41
	15	38
	center	36
45	2	51
	5	46
	10	38
	15	37
	20	36
	center	36
60	2	48
	5	37
	10	35
	15	33
	20	35
	25	36
	center	36
control		35

Spacing class (m)	Distance from ditch (m)	Water-table depth (cm)
<u>OG12</u>		
35	2	66
	5	54
	10	43
	15	42
	center	41
60T	2	71
	5	57
	10	47
	15	42
	20	32
	25	30
	30	29
	40	30
	50	29
	60	30
control		32
<u>OG14R</u>		
30	2	80
	5	74
	10	72
	center	72
control		22
<u>OG14P</u>		
30	2	62
	5	45
	10	39
	center	38
60T	2	56
	5	37
	10	32
	15	30
	20	27
	25	27
	30	27
	40	21
	50	23
	60	23
control		26

Table 14. Mean (3-year) seasonal depths to water table - clearcut sites. (Detailed results are presented in Appendices 1-5.)

Spacing class (m)	Distance from ditch (m)	Water-table depth (cm)	Spacing class (m)	Distance from ditch (m)	Water-table depth (cm)
No site prep.			Burned		
15	2	66	15	2	42
	5	65		5	34
	center	65		center	31
	2	50	30	2	41
	5	43		5	36
	10	40		10	28
	15	38		center	26
	center	34			
			control		17
	2	35			
	5	27	Shearbladed		
	10	23	15	2	42
	15	23		5	39
	20	21		center	38
	25	19			
	center	19	30	2	45
				5	38
		22		10	31
				center	33
			60	2	36
				5	33
				10	31
				15	31
				20	30
				25	27
				center	23
			control		19

Recommendations and Considerations for Spacing Guidelines

Having shown that depth to water table varies with OG, distance from ditch, ditch spacing and ditch depth, it is necessary to select spacings that meet the hydrological objective of drainage, namely to lower the water table. Because growth-response data for this drainage area are not yet available, the recommendations in this report are based on the widest spacings that met this objective, so that ditch-installation costs are minimized. In order to benefit growth, the optimum drainage spacing must result in depths to water that are greater than for the undrained controls. However, if depths are increased too much by using narrow spacings, then overdrainage can occur and peat moisture conditions may become too dry. The influence of ditch spacing on the moisture regime in

Table 15. Summary of peat depths and water levels.

OG	Ditch spacing class (m)	Mean peat depth (cm)	Mean depth to water at spacing center (cm)				Frequency of depths at spacing center (%) (mean of 3 years)		
			1987	1988	1989	Mean	<40 cm	40-50 cm	>50 cm
FORESTED[a]									
11	25	61	52	41	40	44	34	28	38
	40	50	39	35	34	36	70	22	8
	45	44	38	36	34	36	59	25	16
	60	54	38	36	33	36	73	22	5
	Control	47	37	35	32	35	72	25	3
12	35	243	44	37	42	41	44	29	28
	Control	57	36	31	29	32	83	15	2
14 (poor)	30	115	39	38	37	38	64	29	7
	Control	119	25	25	28	26	99	1	0
14 (rich)	30	315	73	70	72	72	2	3	95
	Control	300	26	23	18	22	94	6	0
CLEARCUT[b]									
11/12 (shear-bladed)	15	41	38	36	41	38	59	28	13
	30	50	36	33	31	33	79	17	5
	60	40	28	22	20	23	100	0	0
	Control	130	19	19	19	19	99	1	0
11/12 (burned)	15	35	34	29	29	31	88	11	1
	30	43	30	25	23	26	93	7	0
	Control	41	15	17	20	17	96	3	1
11/12 (no site prep.)	15	73	67	65	65	66	0	5	95
	40	76	34	34	35	34	77	23	0
	55	74	18	19	21	19	100	0	0
	Control	78	19	22	25	22	95	5	0

[a]poor = poor treed fen, rich = rich treed fen
[b]type of site preparation in brackets

Table 16. Hydraulic conductivity measurements.

	K (x10^{-5} cm/sec)	
	0-20 cm	20-40 cm
FORESTED (OG)		
11	519	42
12	471	21
14(poor)	495	49
14(rich)	224	15
CLEARCUT (site prep.)		
None	378	20
Shearbladed	566	28
Burned	429	21

relation to rooting depths is summarized in Table 15. The three categories (<40 cm, 40-50 cm, >50 cm) were based on the assumption that roots would be able to exploit the extra area between the present maximum rooting depth and the new water-table level.

The criteria used to select a spacing for the forested conditions differed between the OGs as a result of different relationships between rooting depths and control water-table depths. The OG11 and OG12 control water tables averaged 7 to 9 cm below the rooting depths (Tables 1 and 15). For these OGs, the recommended spacing would have a water table at the spacing center similar to that of the controls. The elliptical shape of the water table would then ensure that there would be greater depths to water towards the ditches. A frequency distribution similar to that of the controls would also be required. In contrast to the situations for OG11 and OG12, control water tables in the OG14 groups averaged 7 to 12 cm above the rooting depth (Tables 1 and 13). The selection criterion used for OG11 and OG12, a spacing that produced a water table at the spacing center similar to that of the controls, was not applicable to the OG14 groups because of the high control water tables. Instead, the recommended spacings would have a water table at spacing center just below the rooting depth. The frequency distribution should have a higher percentage in the 40- to 50-cm and >50-cm categories than for the controls.

On the basis of the results of this study, recommended ditch spacings for the forested OGs are:

1) OG11, 40-m spacing: The 25-m spacing had a low water table that caused drier peat conditions, and had the greatest frequency of depths within the >50-cm category (Table 15). The 45- and 60-m spacings had water-table levels within 5 to 10 m of the ditch that were not different from those of the control (Table 9). There was no benefit to be gained from these spacings in terms of a lowered water table. The 40-m spacing satisfied the selection criteria, with a spacing-center depth to water 1 cm below that of the control (Table 13), a well defined, elliptically shaped water table (Table 9), and a frequency distribution similar to that of the control.

2) OG12, 40-m spacing: The results showed that the 35-m spacing had a lower water table than was necessary. Because the 35-m spacing and 60T transect had similar water-table depths at the same distances from a ditch (Tables 10 and 13), it was possible to infer from the 60T results that a spacing of 40 m could meet the criteria. (At 20 m from the ditch on the 60T transect, mean depth to water was 32 cm, the same as for the control. Doubling this distance gives 40 m as the spacing.)

3) OG14 (poor treed fen), 35-m spacing: The 30-m spacing was too narrow, as it caused water-table levels to be 5 cm lower than the rooting depth at the spacing center (Tables 1 and 13). This OG was similar to the OG12, 35-m spacing and OG11, 40-m spacing groups (Table 11), indicating that only a slight increase in spacing was required. A 5-m increase was estimated to be sufficient.

4) OG14 (rich treed fen), 35-m spacing: It was difficult to select a proper spacing for this OG because of the differences in depth to water caused by the deeper fibric layer and deeper ditches. If the standard 90-cm-deep ditches were used, it was estimated that, as with the poor treed fen, 35-m spacing would be sufficient. For both OG14 groups, whose peat depths were consistently greater than 100 cm, spacings of 40 to 45 m could possibly be used if ditch depths were greater than 90 cm. This possibility requires further testing.

In clearcut areas, it is advantageous to have a higher water table than in the forest to promote seedling establishment. If site preparation would be done as part of normal regeneration procedures, the 40-m spacing suggested for forested OG11 and OG12 would be adequate for the harvested areas as well. In both the shearbladed and burned areas, the 15- and 30-m spacings had water tables low enough to indicate possible moisture stress.

The spacing recommendations depend, to a certain extent, on the potential growth response of the trees. If growth increased significantly, evapotranspirational demands would increase, which might cause a lowering of the water table. This biological drainage increases with time (Heikurainen and Joensuu 1981). However, the moisture conditions of the peat above even a deep water table need not be limiting to growth. Päivänen (1973) found that for *Sphagnum* with bulk densities of 0.084 to 0.156 g/cm^3, the capillary fringe (within which water moves by capillarity) was 40 to 70 cm. He concluded that this fringe was sufficient to keep the moisture content above the permanent wilting point. Although the bulk densities were similar to those in the present study (Table 1), the higher proportion of non-moisture-retaining feathermoss in the Wally Creek area may result in a narrower capillary fringe. Another approach was taken by Pelkonen (1975, 1976, 1980), who noted that the moisture requirements of trees change not only over the course of their lifespan, but over the course of each growing season as well. He suggested regulating water-table levels by installing dams in ditches.

CONCLUSIONS

Forest drainage in the Clay Belt of northern Ontario has good potential to improve tree growth if management guidelines are followed. The spacing-guideline recommendations made in the present report may be modified in the future as a result of the economic analysis of growth-response benefits versus installation and maintenance costs. It is possible that such an analysis will indicate that spacings wider or narrower than those recommended here will yield higher benefit/cost ratios.

Kaunisto and Päivänen (1985) stated that "... forest drainage must be considered a basic improvement...". For optimum results, it should be part of a comprehensive silvicultural prescription.

ACKNOWLEDGMENTS

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APPENDICES

Appendix 1. Seasonal depths to water table (OG11).

Spacing class (m)	Distance from ditch (m)	Depth to water table (cm)															
		1987					1988					1989					3-year mean
		Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	
25	2	64	0.7	237	34	84	60	0.8	147	38	81	61	1.0	119	35	85	62
	5	57	0.7	238	34	81	49	0.9	167	29	77	47	1.1	136	22	77	51
	10	52	0.8	204	24	79	47	1.1	124	25	75	45	1.5	102	15	82	48
	center	52	1.1	102	31	73	41	1.2	63	23	72	40	1.6	51	20	75	44
40	2	53	0.7	267	18	77	53	0.7	168	25	71	54	0.7	134	33	71	53
	5	51	0.7	238	17	75	48	0.8	147	22	71	46	1.1	118	24	71	48
	10	44	0.6	238	16	65	40	0.6	147	20	64	39	1.1	119	14	67	41
	15	40	0.6	236	18	62	38	0.6	147	15	59	37	1.0	119	12	61	38
	center	39	0.7	134	21	58	35	0.7	84	22	57	34	1.2	67	14	61	36
45	2	52	0.8	162	34	80	49	1.1	103	21	74	52	1.3	85	28	73	51
	5	49	1.0	162	28	80	44	1.2	103	24	74	44	1.6	85	20	78	46
	10	41	1.0	202	18	79	37	1.3	126	16	81	35	1.6	102	9	87	38
	15	40	0.8	202	19	80	37	1.1	126	14	78	35	1.5	102	11	85	37
	20	38	0.9	204	14	73	36	1.3	126	7	95	34	1.5	102	7	77	36
	center	38	1.3	102	13	66	36	1.8	63	9	78	34	2.1	51	9	68	36
60	2	49	1.0	197	24	81	46	1.2	126	20	88	50	1.1	85	27	73	48
	5	40	1.1	196	10	84	37	1.1	126	-3	85	34	1.5	102	0	83	37
	10	36	0.9	204	6	70	33	1.1	126	13	82	30	1.6	102	0	83	35
	15	38	1.0	195	13	79	33	1.0	126	18	78	27	1.1	85	3	55	33
	20	39	0.8	190	17	76	34	0.9	125	15	69	32	1.0	102	11	60	35
	25	39	0.7	197	7	66	36	0.9	125	19	76	34	1.0	102	17	70	36
	center	38	0.8	99	17	63	36	1.0	62	25	67	33	1.1	51	20	54	36
Control		37	0.4	458	8	72	35	0.5	321	6	65	32	0.5	262	9	56	35

[a]n = sample size

Appendix 2. Seasonal depths to water table (OG12).

Spacing class (m)	Distance from ditch (m)	Depth to water table (cm)															
		1987					1988					1989					3-year mean
		Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	
35	2	65	0.9	124	42	86	64	1.4	65	12	83	70	1.3	62	42	91	66
	5	54	1.3	92	20	82	51	1.0	62	32	70	58	1.7	60	27	83	54
	10	42	1.3	101	5	69	41	1.0	51	27	53	46	1.8	60	13	76	43
	15	44	1.5	81	19	69	39	1.4	60	18	56	42	1.7	61	13	64	42
	center	44	2.0	41	22	67	37	1.7	31	21	52	42	2.2	31	18	57	41
60T	2	79	1.3	33	65	93	67	2.0	18	45	79	68	1.8	17	56	81	71
	5	60	2.0	23	48	78	52	1.6	18	39	64	58	2.5	13	43	73	57
	10	45	1.8	30	29	63	48	1.5	18	37	61	48	1.9	17	35	58	47
	15	46	1.1	28	33	56	40	1.0	18	34	50	40	1.7	17	27	50	42
	20	32	1.2	32	20	50	32	0.7	18	27	39	31	1.6	17	18	42	32
	25	32	1.1	23	23	44	30	0.5	18	27	35	29	1.4	17	18	39	30
	30	31	0.8	23	23	37	29	0.5	18	26	34	28	1.1	17	19	37	29
	40	33	1.0	23	24	45	29	0.5	18	27	34	28	1.1	17	20	37	30
	50	31	1.0	30	16	38	28	0.5	18	25	33	28	0.7	15	24	34	29
	60	32	1.1	23	16	41	30	0.4	18	29	34	29	0.8	15	23	36	30
Control		36	0.4	332	9	60	31	0.6	201	18	75	29	0.7	170	10	56	32

[a]n = sample size

Appendix 3. Seasonal depths to water table (OG14, rich and poor treed fens).

Spacing class (m)	Distance from ditch (m)	Depth to water table (cm)															
		1987					1988					1989					3-year mean
		Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	
30 (rich)	2	82	0.5	204	63	104	79	0.6	126	64	95	78	1.1	60	51	92	80
	5	76	0.6	170	55	95	73	0.7	126	55	92	74	1.5	59	41	93	74
	10	73	0.7	204	47	98	70	0.9	126	46	100	72	1.7	59	34	97	72
	center	73	1.0	102	49	93	70	1.2	63	49	94	72	2.6	30	36	96	72
Control (rich)		26	0.9	169	5	54	23	0.8	105	6	45	18	1.1	60	0	39	22
30 (poor)	2	65	0.9	136	30	82	62	1.2	84	30	82	60	1.1	68	31	79	62
	5	46	0.8	136	26	66	47	1.1	84	28	66	42	1.2	68	25	70	45
	10	41	0.7	132	25	58	39	0.9	84	29	65	38	1.1	68	24	62	39
	center	39	0.9	64	26	53	38	1.1	42	26	54	37	1.6	34	17	64	38
60T (poor)	2	62	1.1	34	45	76	55	2.1	21	40	76	50	2.1	17	39	70	56
	5	41	1.0	34	32	54	37	2.0	21	28	65	33	2.0	15	24	49	37
	10	37	1.0	34	27	47	33	1.5	21	23	46	26	1.5	17	16	40	32
	15	33	0.8	34	24	42	30	1.3	21	21	43	27	1.4	17	17	40	30
	20	28	0.9	34	16	37	27	1.1	21	19	40	27	1.3	17	18	39	27
	25	28	1.1	34	19	46	27	1.2	21	19	42	27	1.3	17	19	39	27
	30	28	1.4	34	19	59	28	1.3	21	19	45	26	1.4	17	20	39	27
	40	19	0.7	34	11	28	20	1.0	21	11	31	23	1.6	17	13	37	21
	50	22	0.8	34	8	31	23	0.9	21	16	34	23	1.1	17	15	32	23
	60	23	0.6	34	15	32	23	1.0	21	16	34	23	1.1	17	15	33	23
Control (poor)		25	0.4	198	8	40	25	0.5	126	10	37	28	0.6	102	13	43	26

[a] n = sample size

Appendix 4. Seasonal depths to water table (clearcut OG11/OG12, no site preparation).

Spacing class (m)	Distance from ditch (m)	Depth to water table (cm)															
		1987					1988					1989					3-year mean
		Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	Mean	SE	n[a]	Min.	Max.	
15	2	68	0.9	50	43	76	66	0.9	42	52	76	65	0.9	34	55	78	66
	5	66	1.0	50	44	75	64	1.3	42	43	78	64	1.5	34	45	80	65
	center	67	1.4	25	45	76	65	1.8	21	44	78	65	2.1	17	47	80	65
40	2	50	1.9	50	27	67	49	2.3	42	26	72	51	2.4	34	26	72	50
	5	43	1.6	48	23	60	43	1.9	42	23	65	44	2.1	34	23	64	43
	10	40	1.6	48	19	61	40	1.7	42	21	62	41	2.1	34	22	65	40
	15	38	1.0	48	22	52	38	1.2	42	23	57	39	1.6	34	25	59	38
	center	34	1.0	25	24	42	34	1.3	21	25	49	35	1.8	17	26	50	34
55	2	32	1.0	50	18	44	35	1.0	42	28	50	39	1.3	34	28	59	35
	5	25	0.8	50	10	34	26	1.6	42	11	51	29	1.7	34	10	55	27
	10	21	0.8	50	7	32	23	1.6	42	8	49	25	1.8	34	7	51	23
	15	21	0.7	50	11	36	23	1.3	42	13	44	25	1.5	34	11	46	23
	20	20	0.6	50	9	29	21	1.2	42	12	40	23	1.4	34	10	43	21
	25	18	0.6	50	6	26	19	1.2	42	10	37	20	1.4	34	8	39	19
	center	18	0.8	25	7	25	19	1.6	21	11	36	21	2.0	17	8	39	19
Control		19	0.5	247	1	41	22	0.7	210	2	49	25	0.8	170	2	54	22

[a]n = sample size

Appendix 5. Seasonal depths to water table (clearcut OG11/OG12, burned or shearbladed site preparation).

Spacing class (m)	Distance from ditch (m)	Depth to water table (cm) 1987 Mean	SE	n[a]	Min.	Max.	1988 Mean	SE	n[a]	Min.	Max.	1989 Mean	SE	n[a]	Min.	Max.	3-year mean
BURNED																	
15	2	43	0.7	136	26	60	39	1.1	84	24	58	43	1.6	68	23	67	42
	5	36	0.5	136	25	52	33	0.9	84	24	66	33	1.0	68	19	55	34
	center	34	0.8	68	23	48	29	1.0	42	22	49	29	1.6	34	17	58	31
30	2	45	1.3	136	-5	77	40	1.4	84	18	67	39	1.4	68	1	66	41
	5	35	0.7	136	18	52	29	0.8	84	18	47	30	1.2	68	12	50	36
	10	32	0.9	136	13	57	27	1.1	84	10	55	26	1.2	68	6	53	28
	center	30	1.1	68	13	43	25	1.4	42	11	41	23	1.4	34	9	36	26
Control		15	0.6	295	-2	61	17	0.7	210	0	45	20	0.8	170	-1	51	17
SHEARBLADED																	
15	2	43	0.8	136	25	73	41	1.3	84	28	73	43	1.4	68	22	67	42
	5	40	0.6	136	26	64	37	1.0	84	26	68	41	1.5	68	17	72	39
	center	38	0.7	68	26	53	36	1.4	42	25	60	41	2.3	34	19	66	38
30	2	46	1.1	68	18	67	44	1.4	42	20	62	46	1.8	34	33	67	45
	5	40	0.9	68	26	60	37	1.5	42	19	59	37	1.5	34	21	55	38
	10	34	0.8	68	22	50	30	1.5	42	6	50	30	1.7	34	6	54	31
	center	36	1.3	34	26	61	33	2.3	21	23	62	31	2.7	17	19	58	33
60	2	34	1.0	68	22	54	35	1.2	42	24	55	40	1.6	34	24	61	36
	5	33	0.7	68	25	53	33	1.5	42	22	73	34	1.6	34	18	54	33
	10	32	0.5	67	25	45	31	1.1	42	22	50	31	1.3	34	18	48	31
	15	32	0.5	67	25	41	30	1.0	42	22	47	30	1.1	34	19	45	31
	20	31	0.7	68	19	44	29	0.9	42	22	45	29	1.0	34	19	43	30
	25	30	0.5	68	22	36	26	0.6	42	20	35	24	0.6	34	17	32	27
	center	28	0.6	34	22	33	22	0.5	21	18	27	20	0.5	17	16	24	23
Control		19	0.3	295	7	34	19	0.5	210	8	68	19	0.6	170	5	45	19

[a]n = sample size